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CASUALTY ASSESSMENTS OF PENETRATING WOUNDS FROM BALLISTIC TRAUMA

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14. ABSTRACT

This report identifies areas in which procedures for estimating incapacitation from penetrating wounds can be enhanced. Current methodologies for describing incapacitation, wounds and penetration depth are discussed in detail. Improvements are indicated with reference to the parametric form of the retardation algorithm, ballistic testing, and the manner in which ballistic test data is reduced. Incapacitation estimates using current methodologies are compared with autopsy and battlefield data. The "ballistic dose" (MV3/2) as used in current methodologies to estimate casualties and assess munition effectiveness did not correlate with the degree of incapacitation in these cases. Experimental data generated for spheres penetrating different homogeneous formulations of ordnance gelatin targets could not be accurately described using current methods. An alternative strategy is employed to predict the penetration depth of spheres at various striking velocities and .22 caliber rifle bullets. Analytical predictions for the retardation, yaw, and trajectory of a 19.6 grain flechette are also compared with experimental data as measured in-situ during ballistic tests involving a range of striking yaws and velocities. Experimental data correlated very closely with the analysis.

15. SUBJECT TERMS

INCAPACITATION	BOMB FRAGMENTS	PENETRATION INJURIES	PREDICTING
PENETRATING WOUNDS	BALLISTIC TESTING	WOUNDS AND INJURIES	MODEL
BULLETS(PROJECTILES)	CASUALTY ESTIMATION	BALLISITIC TRAUMA	LIMB TRAUMA
FLECHETTES	CASUALTY ASSESSMENT	WOUND TRAUMA	

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PREFACE

This report identifies areas in which procedures for estimating incapacitation from penetrating wounds produced by bullets, flechettes, and bomb fragments can be enhanced. Current methodologies for describing incapacitation, wounds and penetration depth are discussed in detail. Improvements are indicated with reference to the parametric form of the retardation algorithm, ballistic testing, and the manner in which ballistic test data is reduced.

Incapacitation estimates using current methodologies are compared with autopsy and battlefield data. 373 cases involving civilian handguns and 382 battlefield cases involving 7.62 x 39 mm military rounds are reported. The outcome of 36 cases involving bomb fragments from the Vietnam Wound Data and Munitions Effectiveness Team (WDMET) data base were also compared with existing methodologies for predicting wound severity. All of the reported cases involved wounds to the thorax. The "ballistic dose" ($MV^{3/2}$) as used in current methodologies to estimate casualties and assess munition effectiveness did not correlate with the degree of incapacitation in these cases.

Experimental data generated by the Mission Research Corporation (MRC) for spheres penetrating different homogeneous formulations of ordnance gelatin targets could not be accurately described using the parametric forms of the empirical relations currently employed to predict wound tract depth in human tissue. The reasons for this are discussed in detail and an alternative analytical strategy is recommended.

This alternative strategy is employed to predict the penetration depth of spheres at various striking velocities and .22 caliber rifle bullets. Analytical predictions for the retardation, yaw, and trajectory of a 19.6 grain flechette is also compared with experimental data as measured *in-situ* during ballistic tests involving a range of striking yaws and velocities. Experimental data correlated very closely with the analysis.

The analytical form of the equations used are based on physical relations between the parameters involved and can be independently measured with relevant mechanical property tests. By using relevant mechanical property data for biological tissues in the proposed analytical procedures, the geometry of the wound tract in biological specimens can be determined and compared with autopsy data to assess model fidelity. These procedures will significantly improve the accuracy of wound tract descriptions and incapacitation assessments in humans.

CASUALTY ASSESSMENTS OF PENETRATING WOUNDS FROM BALLISTIC TRAUMA

BACKGROUND

The most comprehensive methodology currently available to assess incapacitation from penetrating ballistic injuries was developed by the Army Research Laboratory [1]. This methodology yields a conditional probability, *P(I/H)*; i.e., the "expected level of incapacitation given the occurrence of being struck by a particular projectile." This conditional probability or expected level of incapacitation is obtained by summing across a population of casualties, the product:

{percentage of incapacitation} x {frequency of occurrence}.

For example, if percent incapacitation is rendered in 25% increments (i.e., 0.25, 0.5, 0.75, 1.0) and the frequency distribution within a population of casualties is:

- 25% of wounded population sustained 25% incapacitation
- 35% of wounded population sustained 50% incapacitation
- 20% of wounded population sustained 75% incapacitation
- 20% of wounded population sustained 100% incapacitation

then,

$$P(I/H) = (0.25 \times 0.25) + (0.35 \times 0.5) + (0.2 \times 0.75) + (0.2 \times 1) = 0.5875.$$

This is the expected level of incapacitation if struck by the projectile common to the wounded population.

1.0 CURRENT INCAPACITATION MODEL

Based on experimentation with various combinations of projectiles, striking velocities, and wound tracts in animals, human bones, and surrogate media: the Army Research Laboratory (ARL) developed a model to predict expected levels of incapacitation based on wounds by single fragments. *Incapacitation* within this context is defined as degradation of a soldier's ability to perform tasks required by a particular combat role. Incapacitation is treated as a function of projectile parameters and initial conditions (type, shape, mass, and striking velocity), the wound (location and tract), and the soldier's tactical role.

Medical assessments are performed in the current methodology to estimate wound severity and resulting biomechanical degradation (in terms of limb dysfunction) for a particular post-wound time. The expected level of incapacitation is estimated by comparing biomechanical requirements of the particular tactical role with the degraded biomechanical capabilities. The detailed procedure for performing these assessments is automated in ARL's *Computer Man* code.

The *Computer Man* code includes the capability to project wound tracts from a number of different fragment types (spheres, cubes, low aspect ratio cylinders and irregular fragments) onto a digitized model of the human anatomy to describe tissues disrupted by a projectile. The model has a data base of wound severity indices based on a consensus of medical opinion and associated with the constituent tissues of the human anatomy.

The biomechanical degradation (expressed in terms of limb dysfunction) associated with a wound is based on the tissue disrupted in the wound tract with the highest severity index. The degradation in limb function is compared with the requirements of four representative tactical roles (assault, defense, supply, and reserve) and various post-wound times (30 seconds to 5-days) to establish a level of incapacitation (0, 25, 50, 75, and 100% corresponding to no incapacitation, minor, moderate, severe, and lethal incapacitation, respectively).

A mathematical function found by ARL[1] to closely approximate *Computer Man* code predictions for the expected level of incapacitation from a penetrating wound and used by the munitions community to assess ammunition effectiveness is:

$$P(I/H) = 1 - \exp[-a(mv^{3/2} - b)^n]$$

In the above, m is the mass of the fragment in grains, v is the striking velocity in feet-per-second, and a, b, and n are parameters whose values depend on the tactical role, post-wound time, and anatomical region (head and neck, thorax, abdomen, pelvis, arms, and legs) struck by the projectile.

2.0 NEED FOR MODEL REFINEMENTS

The current methodology discussed in the previous section can be summarized in terms of the five steps below.

(a) Definition of missile parameters and striking conditions;
(b) Description of the resulting wound;
(c) Medical assessment of the wound;
(d) Biomechanical consequence of the wound; i.e., degradation (rendered in terms of limb dysfunction); and,
(e) Comparison of biomechanical degradation with biomechanical requirements imposed by the particular tactical role under consideration. This results in an estimate of incapacitation.

New insights and more refined assessment tools however have become available which can significantly enhance the fidelity of step b, the wound description, and as a result improve the accuracy of subsequent steps in the methodology.

2.1 The Wound Tract Description

There are four limitations thwarting improved fidelity of the wound tract description in the current ballistic casualty model. These limitations include:

(1) The retardation algorithms used to predict penetration depth are based entirely on empirical relations and therefore only applicable to those projectiles and striking conditions previously tested;

(2) The data base upon which the empirical relations were developed bear a questionable relation to the corresponding human tissue;

(3) The functional form of the retardation algorithms and the format of the existing data base describe penetration characteristics in the low and intermediate velocity regime for spheres (and presumably other projectiles as well) that contradict experimental data for animal tissue and tissue simulants; and,

(4) The projectile motion is idealized as one-dimensional particle motion of the projectile center-of-mass.

The consequence of issue 1 is that the range of application to other projectiles and striking conditions is severely limited. The consequence of issues 2 through 4 is that the predicted penetration depth and geometry of the wound tract is either inaccurate or extremely crude. The fourth issue also limits application of the methodology to symmetric low aspect ratio projectiles, which are not prevalent on the battlefield.

2.1.1 Empirical Derivation of Retardation Algorithms

The predicted wound tract is based purely on empirical data fits and therefore limited in application to the specific fragments and striking conditions which compose the data base. This situation is exacerbated by the user community, which on occasion extrapolates the existing data to other projectile types and striking conditions.

An example of this is the development of a widely accepted flechette model by employing an *equivalent sphere* from the existing data base [2]. In this approach, the terminal ballistics of a flechette striking a bare torso are simulated by assuming that the flechette retards like a sphere with the same diameter as the shank of the flechette and same total mass as the flechette.

Figure 1 shows a comparison between experimental results obtained on a 19.6 grain flechette [3] and an *equivalent sphere* [4] modelled in this fashion. In this figure the equivalent sphere model is shown to closely approximate flechette penetration only for striking velocities between 400 and 550 feet per second (fps). Below 400 fps the equivalent sphere model under-predicts flechette penetration by 50 to 100%. For striking velocities above 550 fps the equivalent sphere model under-predicts flechette penetration by at least 50% and with increasing striking velocity by factors in excess of 2. This would tend to result in a severe under-estimation of the depth of penetration for the flechette and consequent inaccuracies in determination of the *P(I/H)*.

It should also be noted that the comparison in Figure 1 is probably the most favorable that could be achieved with the equivalent sphere model. This is because the flechette data in Figure 1 is for striking conditions with minimal yaw (i.e., where the projected area of the flechette in the direction of motion is approximately the diameter of the shank). This is a highly unlikely configuration for the flechette. As the yaw angle (θ) increases, the projected area increases as the $\sin^2\theta$. This results in a factor of 3 increase in projected area for $\theta = 10$ degrees and a 16-fold increase in projected area for $\theta = 90$ degrees. If the flechette manifests any rotational velocity (which is very likely) the yaw angle of the flechette will change and possibly tumble as it penetrates the target medium.

The scaling procedure invoked in Figure 1 to obtain equivalent sphere data was based on ratios of the projectile ballistic coefficients (β) where β equals the projectile mass divided by the product of the drag coefficient and the projected area of the projectile in the direction of motion.

In Figure 1, data for the penetration of a 341 mg, 0.171 +/- 0.0005 inch diameter sphere was scaled to obtain data for an equivalent sphere representing the penetration of a 19.6 grain flechette. Since only spherical geometries were being considered in the scaling procedure, differences in the drag coefficient of the two projectiles were ignored. This yields a modified ballistic coefficient, β', equal to the projectile mass divided by the diameter squared. For the equivalent sphere, β' equals 1. 35 grams/(0.107 in)^2 = 118 g/sq-inch, and for the experimental sphere data β' equals 11.7 g/sq.-inch. The ratio of the modified ballistic coefficients yields a scaling parameter of 10.1 (i.e., the original experimental data multiplied by 10.1 yields the equivalent sphere data used in Figure 1).

An example of the successful application of this procedure is shown in Figure 3. Figure 2 compares experimental data for the penetration of a 340 mg, 0.168 inch diameter sphere with experimental data for a 91.3 mg 0.158 inch diameter sphere. The experimental data for the smaller sphere was then scaled using this procedure to reproduce the penetration behavior of the larger sphere.

Two cautions should be exercised in applying this procedure. First, the procedure begins to break down as significant differences in Reynolds Number are manifested (above 2500 fps for the spherical projectiles described). Second, spherical projectiles are not perfectly spherical. Also, the manner of launching the projectile alters the diameter of the projectile. For example, in an undocumented experiment conducted by the Mission Research Corporation (MRC), standard BBs were launched using sabots and bore fitting launch tubes. The diameter of the BB striking the target varied by 3% between the two methods resulting in a 5% difference in β'.

2.1.2 Data Base Composed of Ballistic Tests on Materials with Unknown Relation to Human Tissue.

This issue is twofold. First, the original experiments which compose the data base were accomplished on animal tissue or surrogate materials which bear a very uncertain relation to the corresponding human tissue. In fact, with respect to those properties that dictate (to the first order) the penetration characteristics of a missile in the low and intermediate velocity regimes (i.e., physical density, kinematic viscosity, tangent modulus, and ultimate stress and strain); there may be substantial differences between human and the corresponding animal tissues.

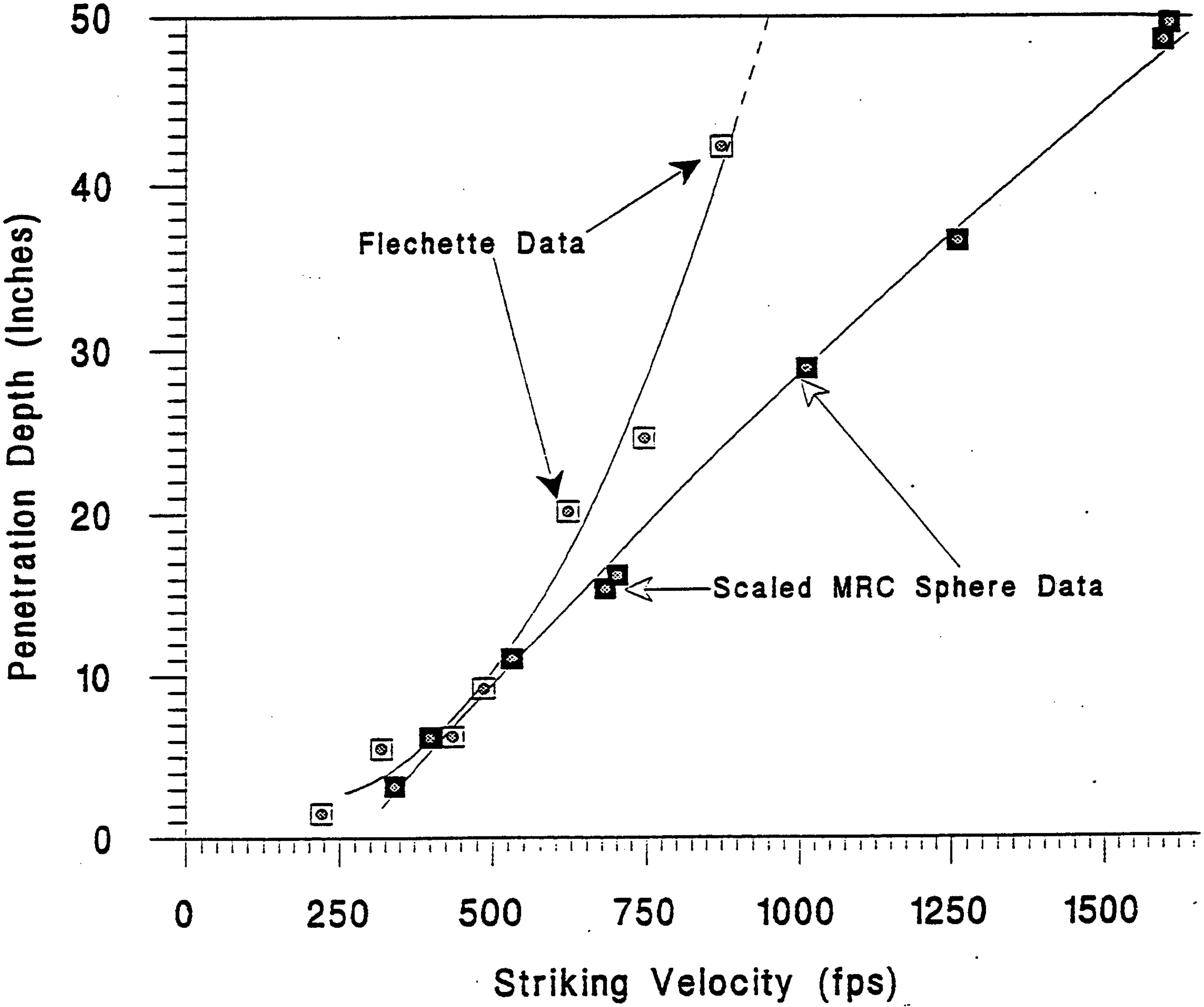

Figure 1. Comparison of an Equivalent Sphere and Flechette Depth of Penetration into 20% Ordnance Gelation [Complied from References 3 and 4].

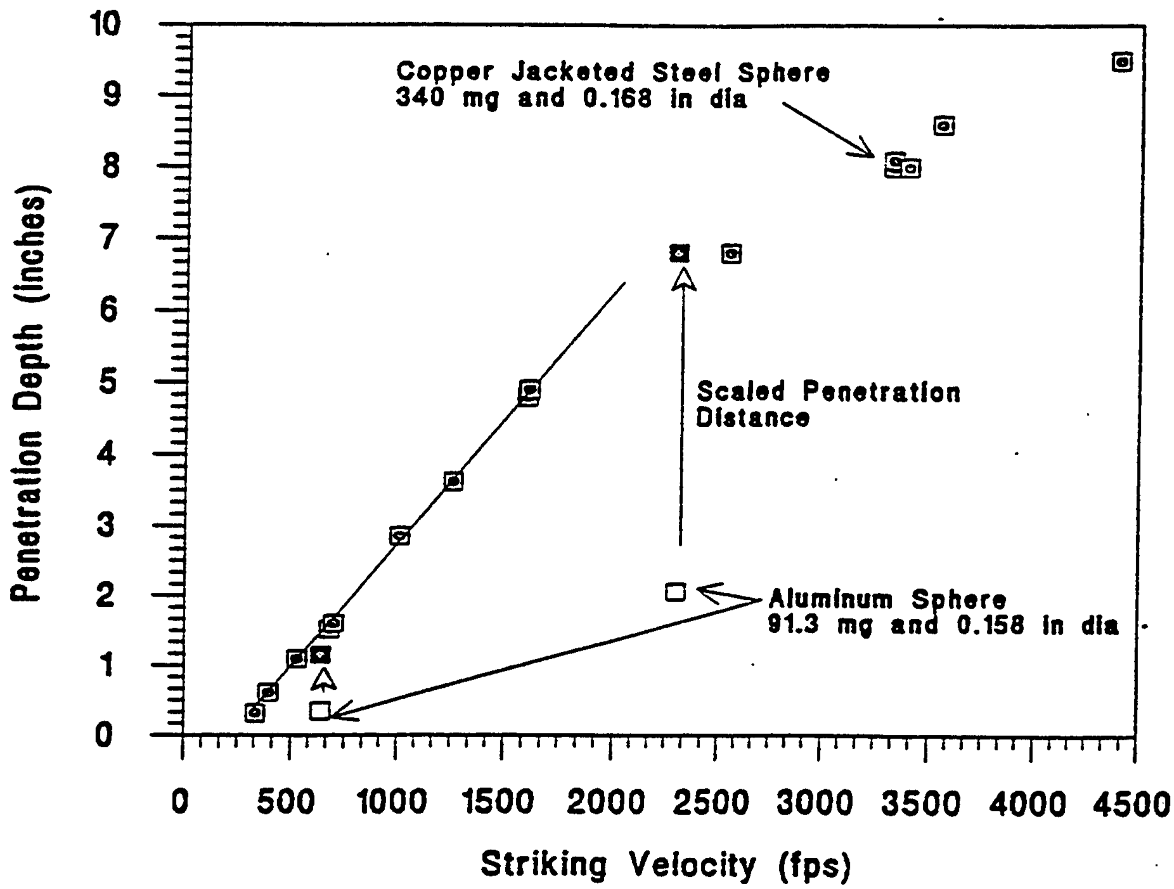

Figure 2. Striking Velocity versus Penetration Depth in 20% Ordnance Gelatin for Standard BB, Aluminum Sphere, and Scaled Penetration of Sphere

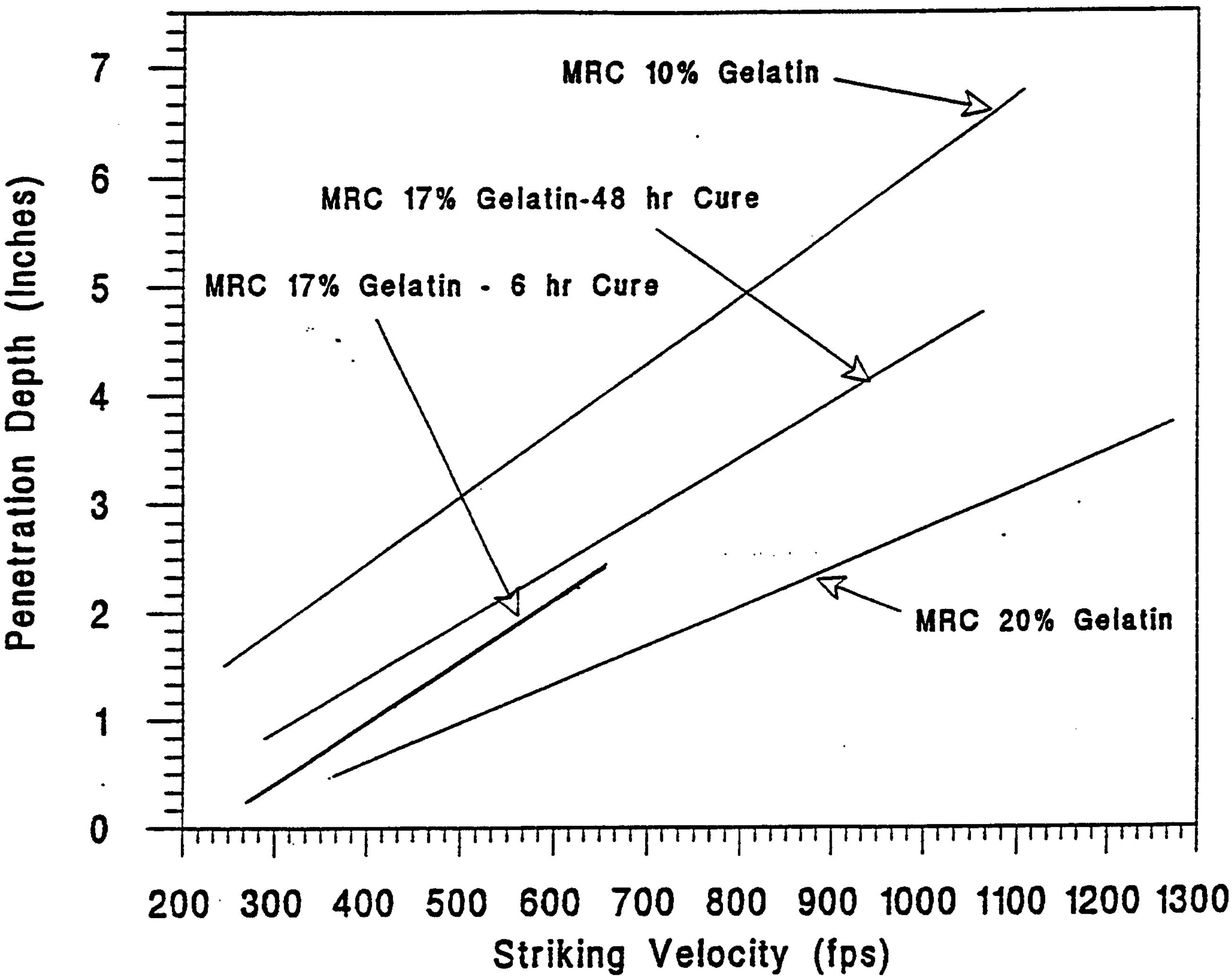

Figure 3. Striking Velocity versus Penetration Depth for Different Gelatin Formulations

An additional concern is related to inadequate resolution of tissue categories in the data base. For example, in the data base for *Computer Man*, retardation constants are provided for the nine tissue categories shown in Table 1. This dictates that tissues with different mechanical properties and retardation characteristics be grouped together for the purpose of describing projectile retardation.

Table 1. Retardation Coefficients Used in *Computer Man* Model.

Model Constants	a_{val}			b_{val}			c_{val}		
Projectile Types	Sphere	Cube	Cylinder	Sphere	Cube	Cylinder	Sphere	Cube	Cylinder
Body Parts									
Skin	0.1226	0.2007	0.2117	0.0	0.0	0.0	0.0	0.0	0.0
Face, Heart	0.1920	0.4536	0.3229	0.0	0.0	0.0	0.0	0.0	0.0
Pancreas, Kidney	0.2422	0.4593	0.3361	0.0	0.0	0.0	0.0	0.0	0.0
Lung	0.1577	0.4037	0.3115	0.0	0.0	0.0	0.0	0.0	0.0
Skull, Vertebra, Bone	0.4545	0.8340	0.5158	0.0	0.0	0.0	753.6E6	761.2E6	920.8E6
Sternum, Joint, Femur	0.3035	0.5809	0.3677	0.0	0.0	0.0	234.1E6	216.6E6	296.2E6
Brain, Eye, Spud Cord	0.2059	0.4830	0.3500	0.0	0.0	0.0	0.0	0.0	0.0
Vertebra, Scapula, Tibia	0.7418	1.1370	1.1110	0.0	0.0	0.0	1257E6	801.7E6	1309E6
Pharynx, Larynx	0.2247	0.7889	0.4234	0.0	0.0	0.0	527.3E6	444.0E6	1220E6

For example, the heart which represents a single tissue category has constituent tissues with widely varying mechanical properties. The ultimate tensile strength of fibers in the cardiac muscle of the left ventricle, for example, are approximately 109 KPa whereas the ultimate tensile strength of the papillary muscles in the right and left ventricles are 223 KPa and 280 KPa, respectively. Similarly, the ultimate tensile strength of heart valves range between 971 KPa and 4 MPa [5].

Figure 3 shows the depth of penetration versus striking velocity for a sphere in 10, 17 and 20% ordnance gelatin. The threshold striking velocity (not shown in Figure 3) is 50 to 75 fps in 10% gelatin versus 150 to 175 fps for the 20% formulation [6].

The 10% ordnance gelatin has a specific gravity of 1.02 as compared with the 20% formulation which has a specific gravity of 1.05. The ultimate stress for both materials differs by less than 10%. The major difference between the penetration characteristics of these two similar materials is alluded to in Figure 4, which shows quasistatic force-displacement curves for 10 and 20% ordnance gelatin in unconfined compression. Notice that for a prescribed load the respective displacements in the two materials differ by a factor of 2 to 4; i.e., the tangent modulus and strain energy required for inelastic deformation is significantly different merely due to a relatively small difference in material formulation.

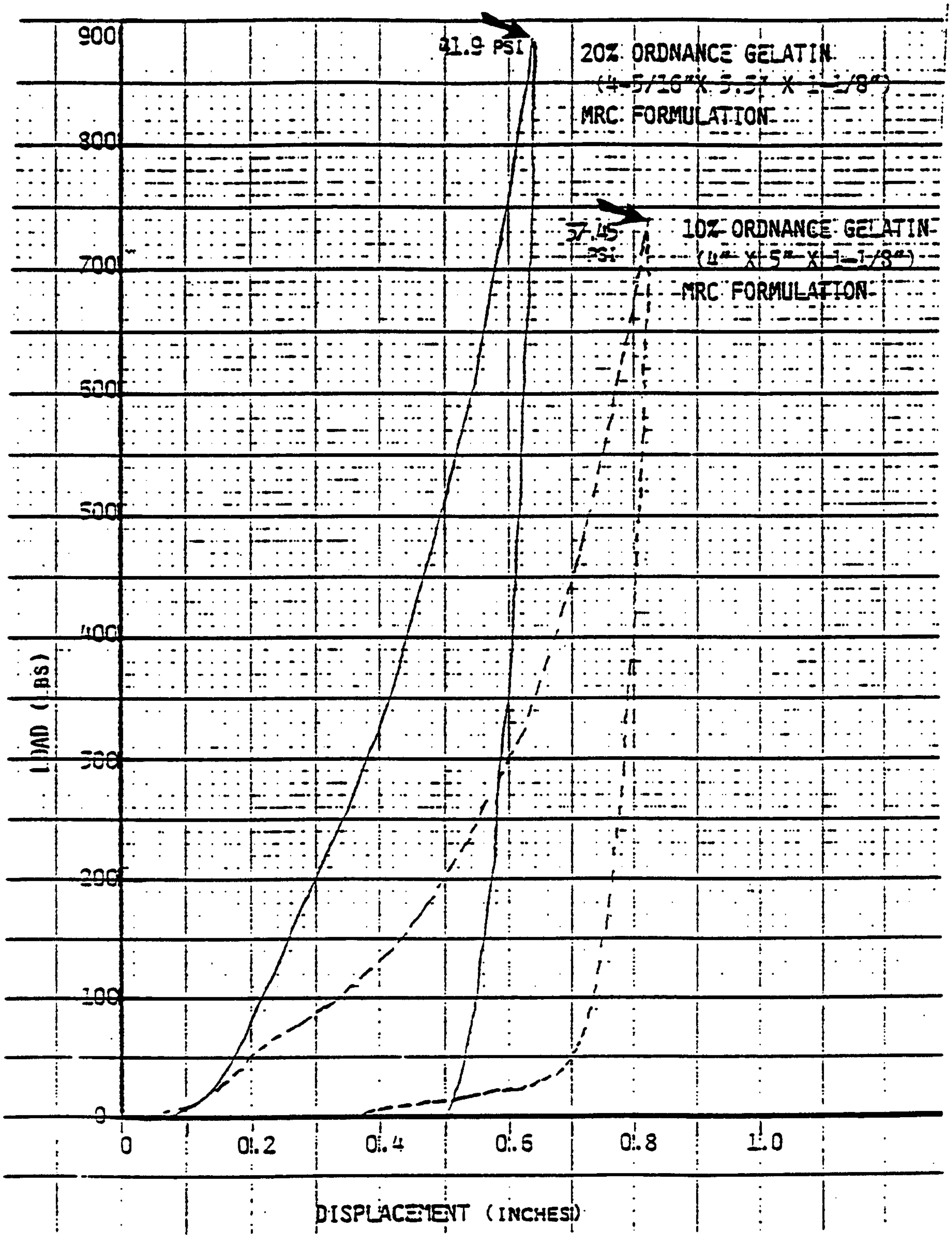

Figure 4. Unconfined Compression Tests of 10 and 20% Ordnance Gelatin [7]

If a 10% difference in the gelatin constituents represent factors of 2 to 3 in penetration depth for spherical projectiles in well controlled experiments on homogeneous material; then presumably there are serious questions relative to employing the existing data base involving animal tissue and surrogate materials and the extension of this data base to humans.

It should also be noted that in the existing data base, it is not clear that the mechanical properties of the target material were measured or verified for consistency prior to ballistic testing. Some of the surrogate materials however, e.g., ordnance gelatin, manifest extreme sensitivity in terms of penetration characteristics relative to the preparation method and precision with which the materials are initially mixed (e.g., extent of gelatin agglomeration and wetting during mixing, heating and cooling rates, whether the residual foam is wiped off the skin of the specimen or allowed to go back into solution), elapsed cure and storage time prior to testing, ambient test conditions (temperature and humidity), and thermal gradients in the gelatin.

For example, 10% gelatin shows a linear dependence in penetration depth to a standard BB of 0.066 inches/degree F between 37 and 47 degrees F [8]. Evaporative cooling of exposed gelatin surfaces can also have dramatic effects on the projectile striking velocity required for initial penetration into the target [9].

A specification test should be performed on the target medium (such as shooting a standard size sphere into the target and comparing penetration depths). Unless this type of specification is implemented, the relation between different tests on similar targets may not be comparable. Figure 5 illustrates this concern and shows the results for ballistic tests accomplished by two different sources. These tests involved penetration of a sphere into two preparations of 20% ordnance gelatin. Note the low scatter of the experimental data for both preparations. The difference in these two sets of data is ascribed to dissimilar kinematic viscosities in the gelatin targets. The source of this disparity in gelatin formulation was never established.

In the case of the edging data base, not only is there considerable concern relative to target material properties (both in terms of the value and consistency of these properties) but also a large scatter of experimental results is evident (see Figure 6 compiled from Reference 10).

2.1.3 Functional Form of Retardation Algorithm and Format of Data Base Not Appropriate for Low and Intermediate Velocity Regimes of Projectiles

The functional form of the retardation algorithm in *Computer Man* when used in conjunction with the existing data base for spherical projectiles results in predicted penetration depths as a function of striking velocity that are contrary to experimental data involving ballistic tests of spheres into animal tissue [11,12] and tissue simulants (ordnance gelatin [13,14] and glycerin soap [15])

This is particularly evident in the low and intermediate velocity regime and is especially serious since a projectile retards very quickly in striking biological tissue at high velocities. The major portion of the wound tract is therefore produced by the projectile while travelling at low and intermediate velocities which is where the analytical procedures currently in use and the existing data base are particularly questionable.

Since analytical procedures employed to describe the wound tract in step b of the current methodology appear limited relative to predicted penetration depth for geometries as simple as spheres into homogeneous tissue simulants; then conclusions from subsequent steps of the methodology must be questioned. This issue will be discussed in more detail in Section 3.

2.1.4 Motion of Projectile Idealized Using One-Dimensional Rigid Particle Dynamics.

The wound tract in *Computer Man* is established by idealizing the projectile as a particle with a lumped mass concentrated at the projectile center-of-mass. The trajectory of the projectile center-of-mass is assumed to be a straight "shot line" with the penetration depth established by various assumptions used in conjunction with one-dimensional equations of motion for a particle. The diameter of the wound tract is presumed to be a characteristic dimension of the projectile which remains constant.

Real projectiles do not follow straight trajectories (see Figure 7) and retard due to various factors which are intimately associated with the rotational kinematics of the projectile as it penetrates tissue (e.g., changes in the projected area and geometry of the projectile in the direction of motion)[1].

The convolution of projectile and target media properties into lumped empirical coefficients, which are applied to one-dimensional particle motion, necessitates the use of a discrete data base for each particle type and tissue category to be considered. This severely limits the utility of the data base for high aspect ratio projectiles, yawing projectiles, and projectiles which strike obliquely (which are the most likely scenarios of interest). This approach, due to the large number of tests that would be involved, also makes it impractical to consider more than a very limited set of tissue categories in constructing the wound description.

While it could be argued that this issue *may be* of minor significance for low aspect ratio projectiles (of the type already included in the data base and *Computer Man)* where the projected area and geometry do not vary in an extreme manner due to rotational motion and therefore in some sense can employ lumped average values; the issue is certainly of first order significance for asymmetric projectiles or projectiles which do not have a 1:1 length to diameter ratio.

[1] The large experimental scatter associated with the existing data base is probably related to not explicitly accounting for the rotational kinematics of the projectile during penetration.

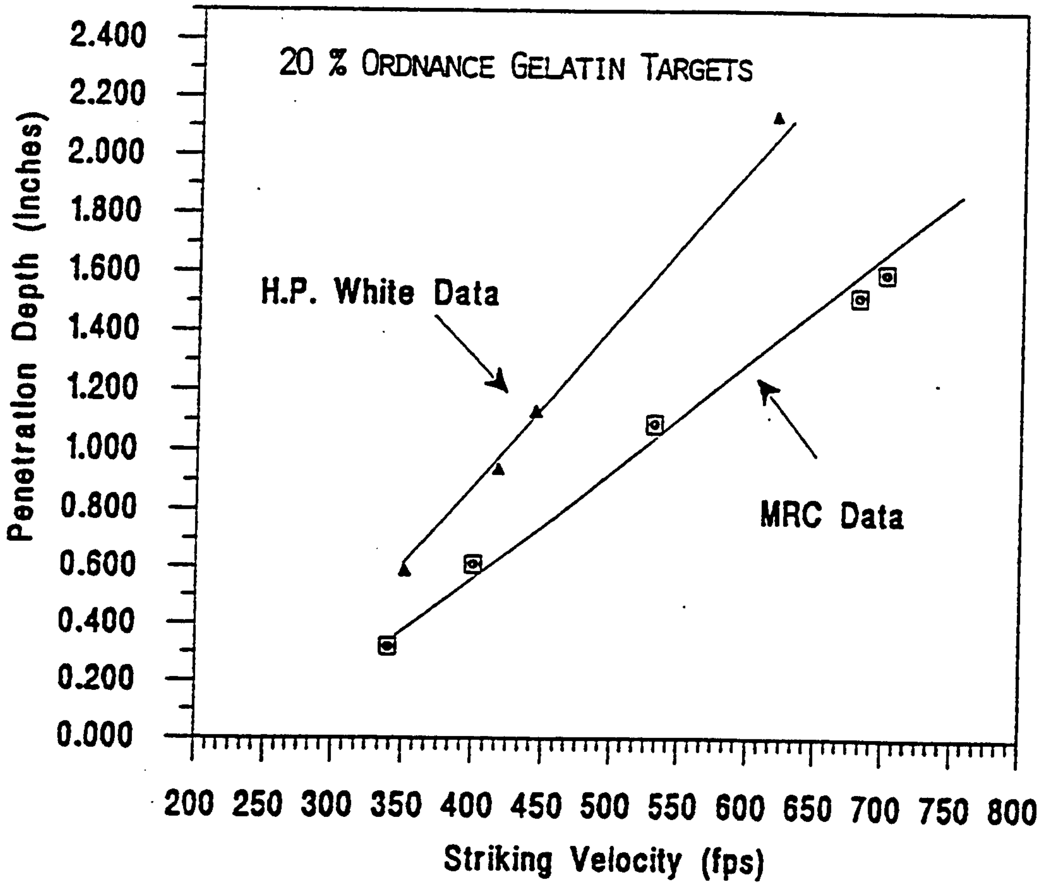

Figure 5. Ballistic Penetration of Standard Sphere into 20% Ordnance Gelatin Acquired from Two Different Sources.

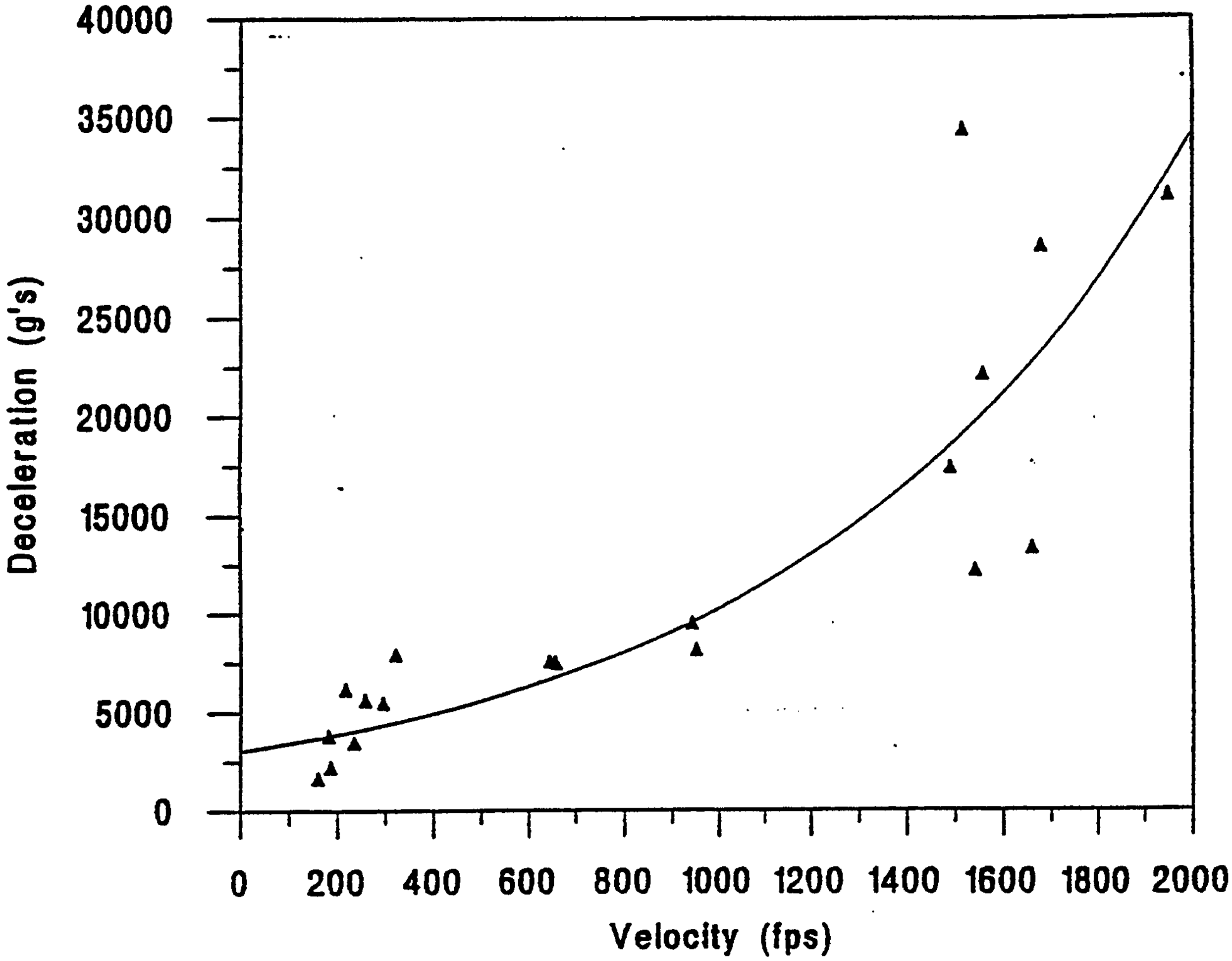

Figure 6. Deceleration in G's versus Striking Velocity in fps for 17 Grain Flechettes.

2200 FPS Striking Velocity

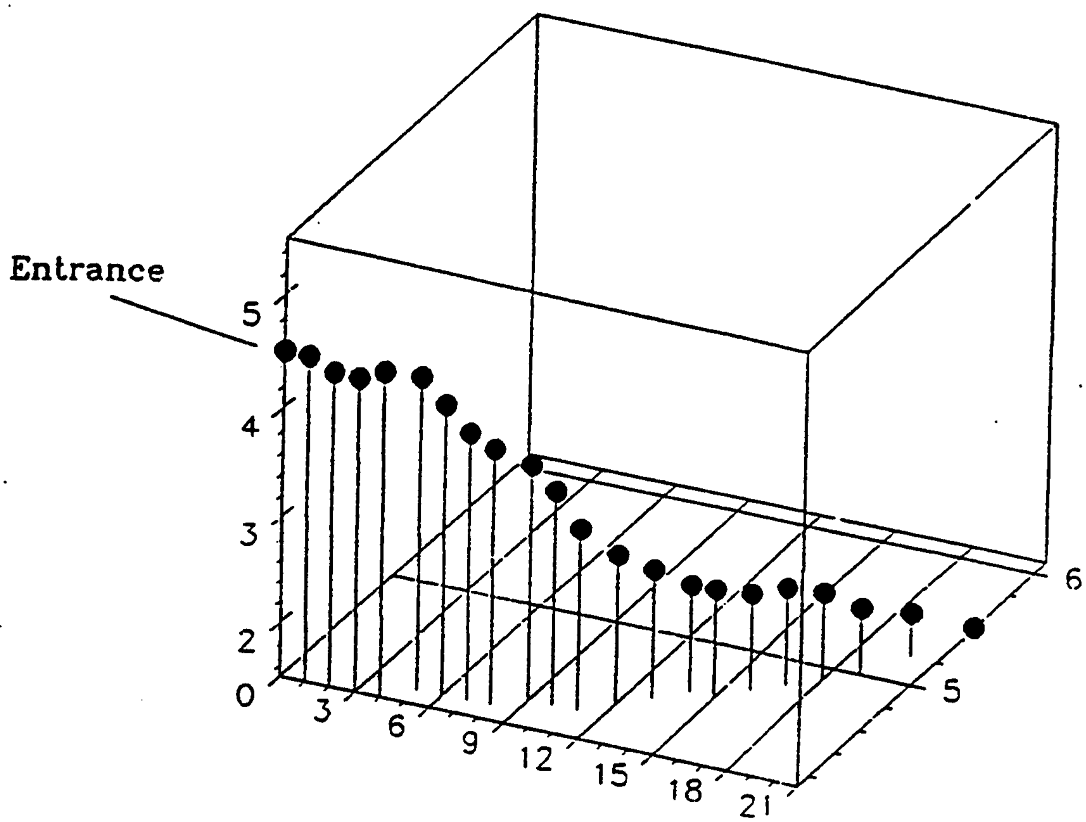

Figure 7. Trajectory of Projectile Fired From AK47 into 20% Ordnance Gelatin.

2.2 Incapacitation Assessment

Given uncertainties relative to the procedures employed in step b to describe the wound tract geometry and dimensions, a discussion of subsequent steps in the methodology is perhaps moot. However, it can be observed that in comparing autopsy data involving fragments, hand gun, and rifle bullets; the expected levels of incapacitation do not seem to correlate to the notion of a ballistic dose, $MV^{3/2}$, used by ARL and others to estimate expected levels of incapacitation.

Figure 8 renders a plot of *P(I/H)* versus ballistic dose for the 30 second assault and 12 hour supply mission given the thorax being struck by a projectile. Figure 9 compares the *P(I/H)* for the entire body for 30 second and 5-day post wound times where a minimal difference is seen below 10^7 and a 15 to 20% difference is seen above 10^7. Figure 10 was created using information from the Wound Data and Munitions Effectiveness Team (WDMET in Vietnam [16]). It includes data for penetrating wounds of the thorax by random fragments. Table 2 lists the injury classification used by WDMET. Figure 10 indicates a lack of correlation with ballistic dose. Figure 11 shows a similar result for handgun data [17] and data from military rifle rounds [18].

In Figure 11 the data[2], based on autopsy and police department statistics for handguns, refers to immediate "stopping power:" that is the probability that someone if struck in the thorax will be incapable of returning fire. In that sense, the handgun data represents a lower bound to the 30-second assault *P(I/H)* since it excludes incapacitating injuries of those people not immediately disabled which wound increase the *P(I/H)*. The data point for the 7.62 military round represents lethality independent of post-wound time. From this context, this data point is probably more representative of a *P(I/H)* corresponding to the 5-day post-wound assault (Figure 9) or 12-hour supply curve (Figure 8).

In determining the WDMET *P(I/H)*, the WDMET severity classifications had to be related to the percentage of incapacitation used in the current methodology. The following assumptions which were designed to yield the range of highest and lowest *P(I/H)* values were made to accomplish this.

<u>Upper Bound Assumptions for Thoracic Wounds</u>

- KIA and Severe were equivalent to 100% incapacitation
- Moderate was equivalent to 75% incapacitation
- Minor was equivalent to 25% incapacitation

<u>Lower Bound Assumptions for Thoracic Wounds</u>

- KIA was equivalent to 100% incapacitation
- Severe was equivalent to 75% incapacitation
- Moderate was equivalent to 50% incapacitation
- Minor was equivalent to 0% incapacitation

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[2] In Figure 2, the adult males in the lighter weight categories corresponding to the various handgun ammunitions were all wearing winter clothing. This may account for the discrepancy in *P(I/H)* for the different weight classes.

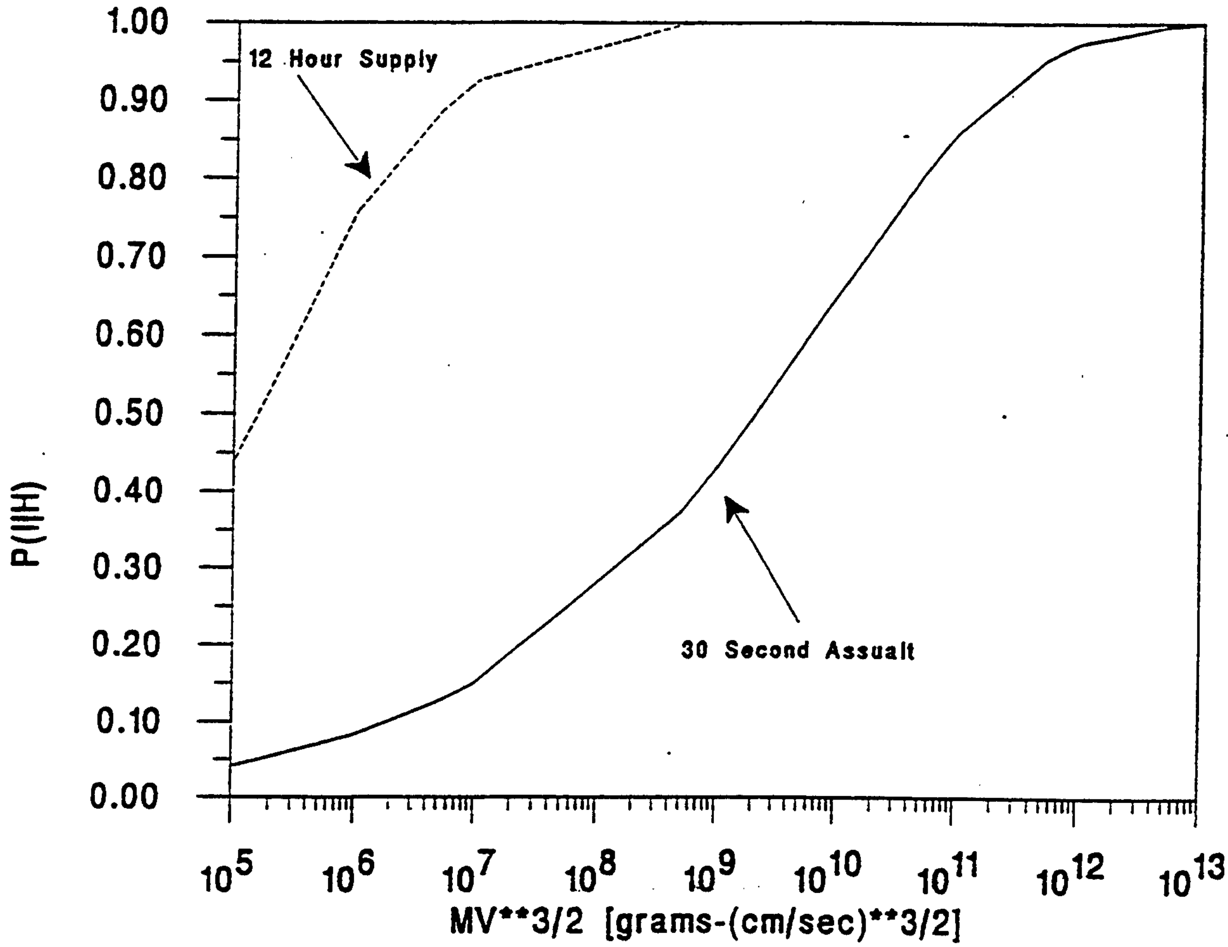

Figure 8. Conditional Probability of Incapacitation Given a Random Steel Fragment Incident of the Thorax.

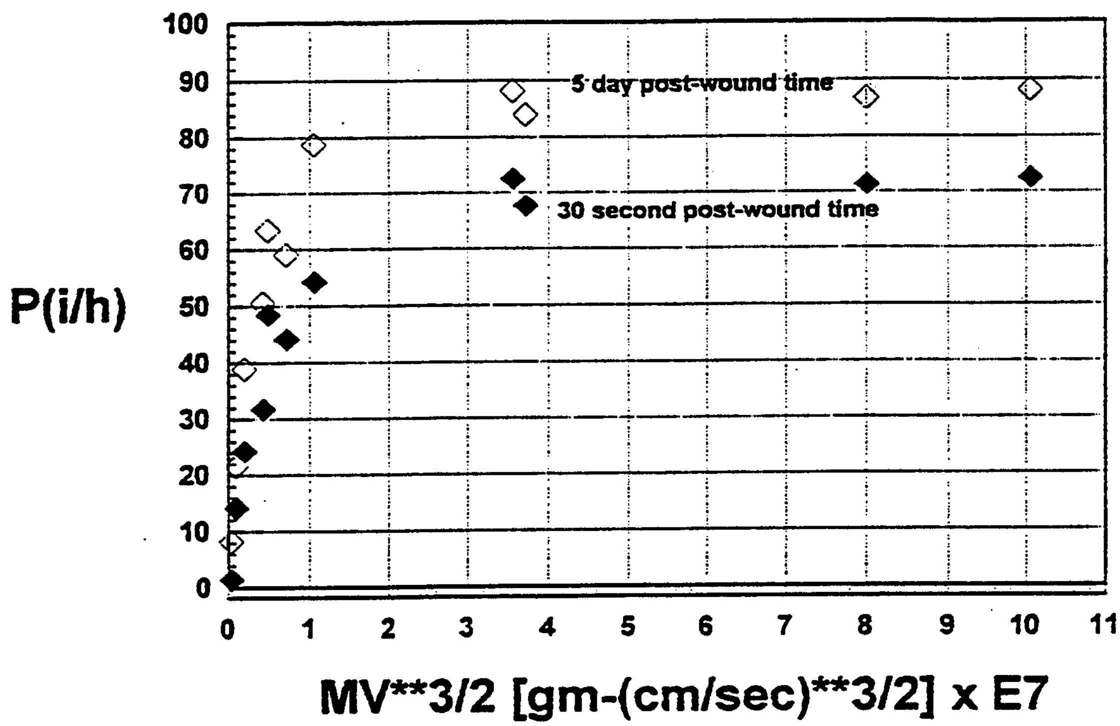

Figure 9. Envelope for ARL Curve Fits of Whole Body Performance Degradation during Infantry Assault and Two Post-Wounding Times.

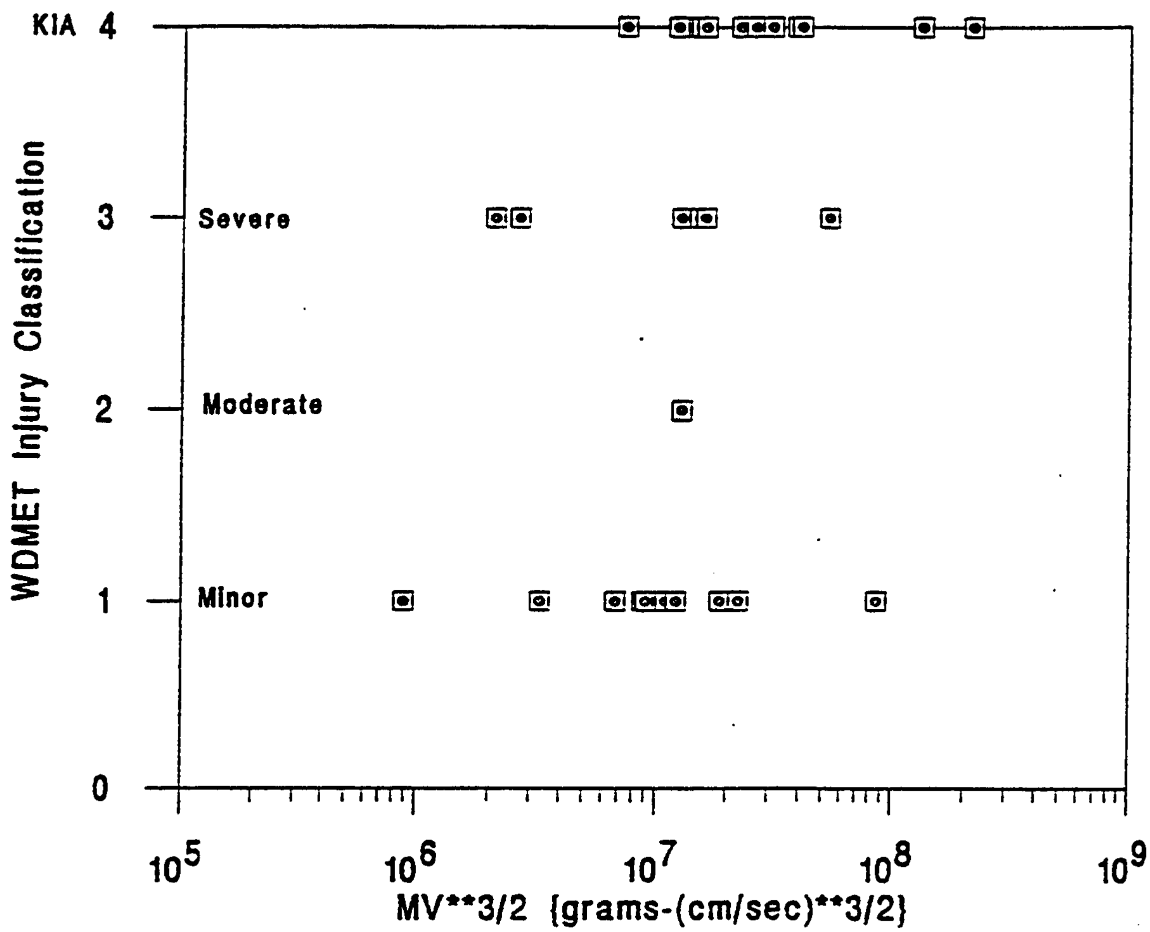

Figure 10. Wound Severity versus Ballistic Dose for Random Fragment Incident on Thorax.

Table 2. Wound Severity Classifications used by WDMET for Bullet and Fragment Cases [IS]

I. KIA = Death under 50 minutes.

II. SEVERE = Major surgery required - Craniotomy
Laporatomy with repair
Thoracotomy with repair
Major Amputation
DOW: Death exceeding 50 minutes.
Traumatic amputation of an extremity.
Major arterial injury: Femoral artery.
Major maxilla - facial injury.
Comminuted fracture femur, humerus, pelvis, radius and ulna, tibia and tibia.
Severed nerve (Sciatic, Brachial plexus)

III. MODERATE =
Over 5 cm depth of penetration in muscle other than thoracic and abdominal wall.
Enucleation of eye.
Extensive debridement.
Arterial injury other than femoral, intracranial, intrathoracic, intra-abdominal.
Other bony damage (except fingers, toes, and nose).
Skull fracture not requiring craniotomy.
Amputation: Hand or foot.
Other nerve damage.
Tube Thoracotomy

IV. MINOR =
Amputation, finger - toe.
Superficial debridement.
Fracture fingers, toes, and nose.
Returned to duty within 24 hours.

Note: Although "KIA" is listed separately, it is probably equivalent to "SEVERE." An early death may not actually reflect the physical severity of the wound as it may be from a secondary effect, such as aspiration of blood.

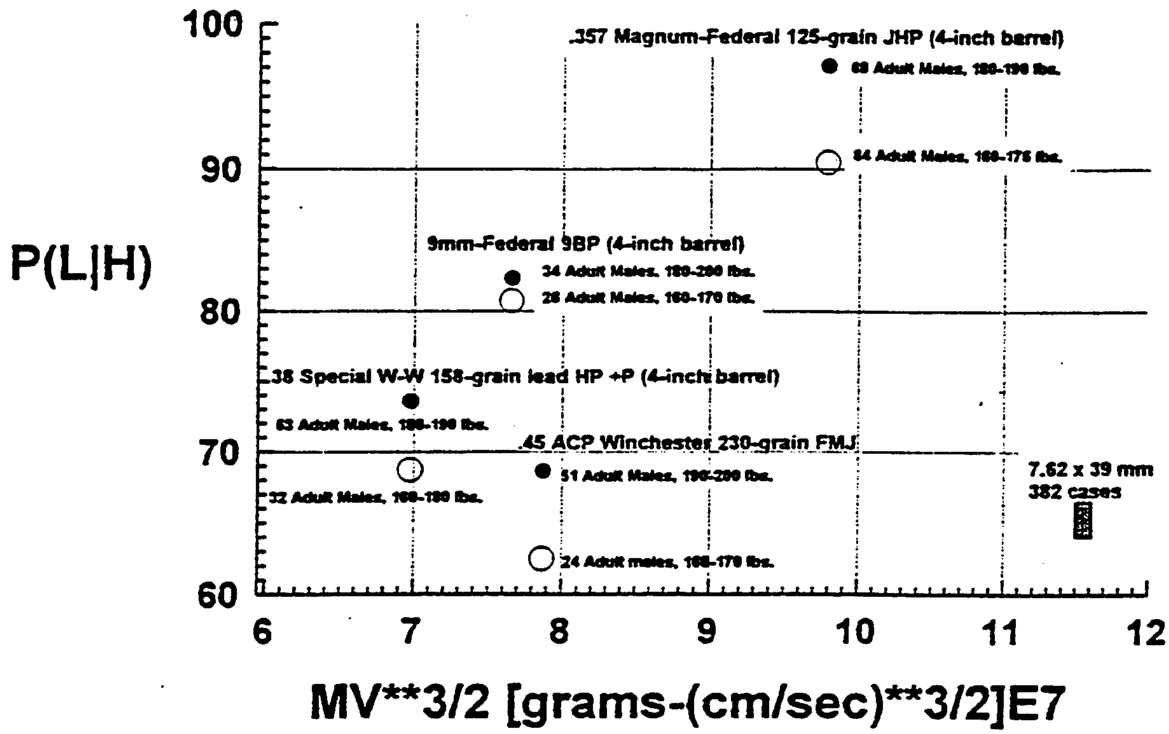

Figure 11. Lethal Probability of Various Ammunition Given a Penetrating Wound of the Thorax.

Table 3. Comparison of Ballistic Dose ($MV^{3/2}$) and *P(I/H)* Using Current Methodology and WDMET Data

$MV^{3/2}$ (gr-fps$^{3/2}$)	2×10^8	2×10^9	2×10^6
Minor	14	9	2
Moderate	1	0	0
Severe	7	6	0
KIA	14	6	2
Total Cases	36	21	4
Predicted *P(I/H)*	0.9	0.85	0.25
WDMET Data *P(I/H)*	0.55-0.7	0.5-0.6	0.375-0.5

Three observations can be made with reference to Table 3 and seem to apply to Figures 10 and 11 as well. First, there is not a very good correlation between the severity of the wound and the ballistic dose. Second, in each of three ballistic dose categories, there are approximately as many minor injuries as KIA. Finally, if we compare the *P(I/H)* over the range of ballistic doses: using the current methodology, the value of *P(I/H)* varies by 65% as compared with the WDMET data where the *P(I/H)* varies by 17.5% using maximum upper bound *P(I/H)* and the minimum lower bound *P(I/H)*. Together, Figures 10 and 11 represent data from 791 battlefield cases which do not appear to support ballistic dose as a measure of wound severity. The fact that the notion of a ballistic dose correlates with *Computer Man* predictions adds to the uncertainty previously discussed in Section 2 relative to the procedures used in *Computer Man* to describe wounds.

3.0 SOLUTIONS

The major problem associated with the wound tract description in the current methodology revolves around the procedures and associated assumptions employed to describe projectile retardation in the various tissue categories. The methodology assumes a parametric form of the retarding force, *F(v)*, as a function of the instantaneous velocity of the projectile, *v*. In the case of *Computer Man* and similar methodologies, the retarding force is assumed to be a quadratic function of the instantaneous velocity of the projectile,

$$F(v) = av^2 + bv + c \qquad (1)$$

In the above, *a, b,* and *c* are empirically determined constant coefficients.

The instantaneous velocity of the projectile as a function of penetration depth, *x*, is obtained by integrating *F(v)* to obtain *v(x)*; i.e.,

$$F = ma = m\left(\frac{dv}{dt}\right) = m\left(\frac{dv}{dx}\right)\left(\frac{dx}{dt}\right) = m\left(\frac{dv}{dx}\right)v \qquad (2)$$

If we let $F(v)/m = f(v)$; then,

$$f(v) = \left(\frac{dv}{dx}\right)v \;\Rightarrow\; \frac{dv}{dx} = \frac{f(v)}{v} = a'v + b' + \frac{c'}{v} \qquad (3)$$

which may be integrated to obtain $v(x)$. The coefficients a', b', and c' are empirically determined.

The depth of penetration, δ, is established by determining the x such that $v(x) = 0$. In *Computer Man*, δ is established for x such that $v(x) = 0 + \varepsilon$, where ε is approximately equal to 20 fps.

There are three fundamental problems with this approach.

(1) The parametric form of the retardation force is assumed to be quadratic. According to MRC experimental data, this represents an extremely poor fit to the data particularly in the intermediate velocity regime and yields the wrong functional form for $\delta(v)$.

(2) Since $\delta(v)$ depends on the integral of $f(v)$, errors -- which are particularly evident in the intermediate and low velocity regime -- accumulate yielding erroneous predicted total penetration depths.

(3) The data base employed by the current methodology (see Table 1) assumes that b is identically equal to zero for all tissue categories and c is identically equal to zero for all soft tissue categories (except the pharynx and larynx). However, it is the linear and constant terms associated with the retarding force which dictate to the first order, the behavior of the projectile in the intermediate and low velocity regimes.

The approach to correct the problems above rely on: (1) Measuring $\delta(v)$ and differentiating to obtain $f(v)$; (2) Assuming the parametric form of $f(v)$ at high and low velocities to establish the asymptotic behavior of $\delta(v)$; (3) Employ matched asymptotic expansions of the high and low velocity asymptotes to establish $\delta(v)$ for intermediate velocities; and, (4) Employing a data base of tissue mechanical properties and $\delta(v)$ for penetration of spheres into a standard well characterized target media.

This approach has been successfully employed in modelling the retardation, yaw, and total depth of penetration for 19.6 grain flechettes into 20% ordnance gelatin. Figure 12 shows a comparison between experimental and predicted results for $v = v(x)$ [3].

The advantages of the advocated approach are manifold. First, the $\delta(v)$ can be directly related to fundamental mechanical properties of the target media. Therefore, if the functional form of $\delta(v)$ is correct for a surrogate material which phenomenologically is similar to soft tissue subject to ballistic impact; then, by substituting the appropriate parameters obtained from a data base of mechanical properties for tissues, the penetration behavior of a projectile into the various human tissues should be accurately represented. Further, this can be accomplished for any number of tissue types up to the maximum resolution of the tissue property data base. A data base which was developed over the course of 25 years by the Kyoto Prefectural University of Medicine in Japan already exists which documents many of the relevant elastic and strength-properties-of fresh unembalmed cadavers [5] and can be exploited for this purpose.

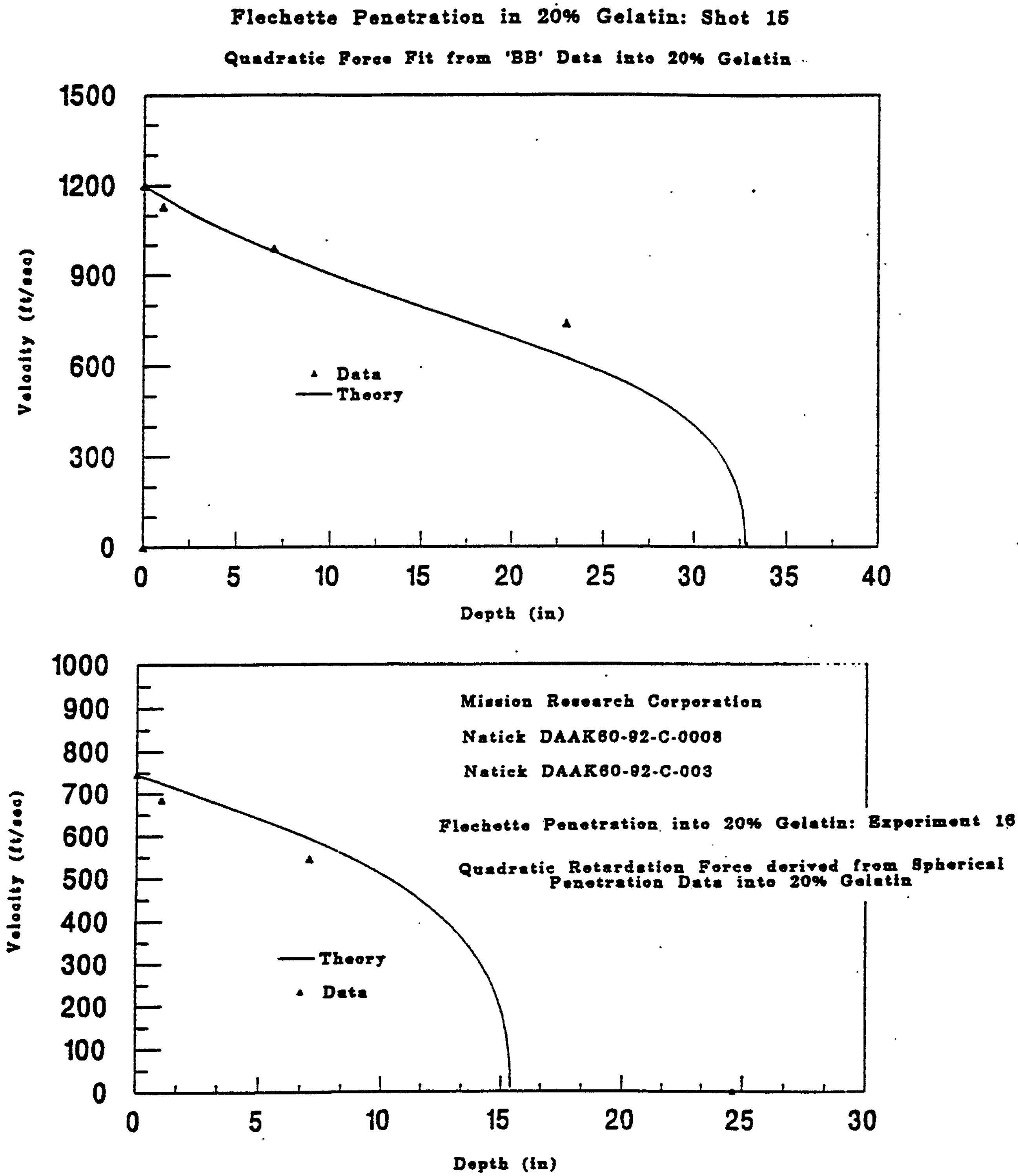

Figure 12. Velocity versus Depth of Penetration of a 19.6 Grain Flechette into 20% Ordnance Gelatin

Another advantage of the proposed approach is that when analytical models are employed, various striking conditions and projectiles can be modelled. The existing approach can only be applied to the projectiles and striking conditions tested.

The suggested approach requires a data base which includes total depth of penetration as a function of striking velocity for spherical projectiles on a standard target medium. The current methodology employs a data base of retardation coefficients which describe the instantaneous velocity of the particular projectile of concern versus depth of penetration. The data associated with the later approach is inherently inaccurate and resource intensive to acquire as compared with the proposed approach which is relatively inexpensive and inherently accurate.

Finally, the suggested approach requires differentiation of $\delta(v)$ to obtain $f(v)$ as opposed to integration of $f(v)$ to obtain $v(x)$. The suggested approach can also be shown to be exact for a known $\delta(v)$. Since the suggested approach involves differentiation rather than integration, it is also very forgiving of inaccuracies since errors do not accumulate as would be the case in the current methodology which involves integration of an assumed functional form for the retarding force. As discussed above and elaborated upon below, the assumed functional form for the retarding force in the current methodology does not yield a good fit of experimental data for $\delta(v)$ involving spheres penetrating animal tissue or tissue simulants (ordnance gelatin and glycerin soap).

3.1 Inversion of Experimental Data to Obtain Retarding Force

During penetration by a projectile into a target, a retardation force is developed due to contact by the projectile with the surrounding medium. This retardation force decelerates the projectile and depends on the kinematic state and under certain conditions the kinematic history of the projectile during penetration. For example, in the case of penetration velocities, v_p, which are much lower than the speed of sound in the target medium, c_p; the retarding force is approximately equal to the static compressive fracture threshold of the material and hence may be regarded as a material constant, c_f. Alternatively, when the penetration velocity is comparable to c_p, the target medium behaves like a fluid and the force of resistance, F, is no longer a material constant but depends on the local kinematics of the projectile during penetration.

Typically, studies accomplished relative to projectile penetration into fluid-like target media assume that the character of F depends on the quasistatic steady-state fluid drag on the projectile. In these investigations, F is proportional to v^2 where v is the steady state velocity of the flow. Since F is the surface integral of the contact forces over the contact area, contact areas may not only depend on the instantaneous velocity of the projectile but also on the history of the loading. Contact areas also depend on the locations of boundary layer separations.

A semi-analytical approach which circumvents the theoretical difficulties above is therefore proposed. This approach provides an estimate of the retarding force for a given target medium and projectile combination as a function of various striking conditions. This approach requires an experimental data base containing penetration depths and corresponding striking velocities for the target media of interest. The proposed approach also defines relationships between parameters in the analytical model and physical parameters that can be independently measured.

This enables extension of the analysis to materials where material property data is available but relevant penetration data may not be available.

The rationale for the approach begins by assuming that even in an unsteady problem, the retarding force depends only on the instantaneous velocity of the projectile; i.e., $f = f(v)$. Further, the projectile is idealized as a rigid ensemble of spherical particles so that the retarding force can be determined by integrating the forces on the constituent particles over the surface of the projectile. An experimental data base is therefore required as a basis for determining the force on one such spherical particle. The problem of determining the retardation force on a projectile penetrating a given target medium has therefore been reduced to the problem of determining the retardation force per unit mass, f, on a spherical projectile where f is an unknown function of the instantaneous velocity of the spherical projectile inside a target. The problem of penetration by a spherical projectile inside a target is schematically shown in Figure 13.

In order to implement this approach, we assume that we have an experimental data base relating the distribution of the penetration depth function $\delta\,(v_0)$ as a function of striking velocity, v_0,. Further, the low and high velocity behaviors of $f(v)$ *are* assumed to be known and given by

$$\lim_{v\text{-}0} f(v) = c_f, \quad \lim_{v\text{-}c_p} f(v) = \alpha v^2 \qquad (4)$$

In (4), both c_f and α can be shown to depend on material properties of the target.

First, let an exact relation be established between the two functions, $\delta(v)$ and $f(v)$ introduced above. The equation of the center-of-mass (CM) of the projectile is given by (cf. Equations 1 through 3):

$$v\frac{dv}{dx} = -f(v) \qquad (5)$$

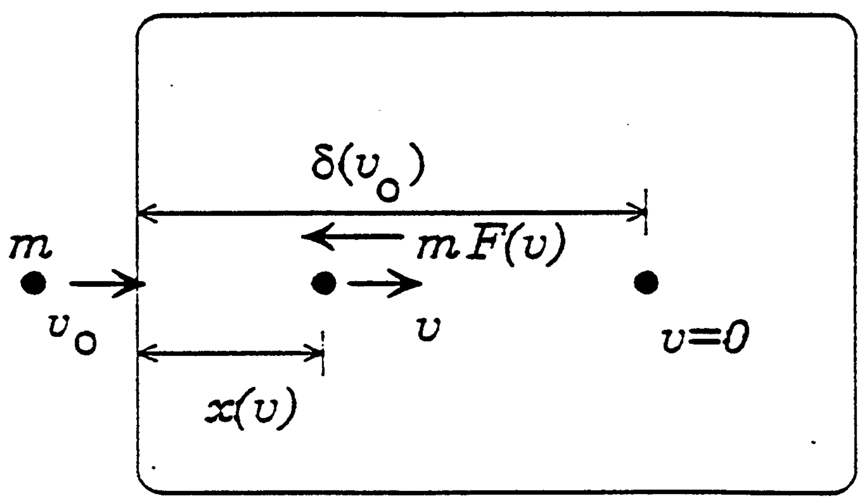

Figure 13. Schematic of Spherical Projectile Penetrating a Target

Integrating (5) from $x = 0$ to $x = \delta$ yields

$$\delta(v_o) = \int_0^{v_0} \frac{vdv}{f(v)} \qquad (6)$$

Since (6) is valid for all v_0, the following is obtained after differentiation of (6) with respect to v_0.

$$f(v) = \frac{v}{\frac{d\delta}{dv}} \qquad (7)$$

Equation (7) is valid for all values of the local velocity v of the projectile inside the target and establishes the exact relation between the retardation force per unit mass, $f(v)$, and the penetration depth, δ. Equation (7) can be used to estimate $f(v)$ from the experimental data base of $\delta = \delta(v)$ as shown in the next section.

3.2 Determination of the Retarding Force

The proposed methodology for obtaining analytical representations of the retarding force is described for various projectile penetration velocities on tissue simulants. A characteristic of these surrogate materials, in particular ordnance gelatin, is that at high penetration velocities, the target media behaves as an inviscid incompressible fluid. At low penetration velocities, the target media behaves as a viscoplastic solid. At intermediate velocities, the target media behaves as a mutiphase viscous fluid. This dramatic variation in mechanical behavior with projectile penetration velocity gives rise to profound differences in the nature of the retarding forces on the projectile. Sections 3.2.1 through 3.2.3 discuss a strategy to obtain the necessary analytical representation of the retarding force so that penetration depth of a projectile can be accurately estimated. Section 3.2.4 contrasts the proposed methodology with shortfalls in the current methodology.

3.2.1 Low Projectile Penetration Velocities.

Rearranging Equation (7),

$$d\delta = \frac{vdv}{f(v)} \qquad (8)$$

using the first equation in (4), and integrating yields:

$$\lim_{v-0} \delta(v) = v^2 \qquad (9)$$

Hence, in the low velocity range $\delta(v)$ can be expressed in a Taylor's series expansion as

$$\delta(v) = v^2\,(a + bv + cv^2 + \ldots) \qquad (10)$$

The constants, a, b, c.... in (10) can be estimated by dividing the experimental data by v^2 and fitting a polynomial to the reduced data. The relation between the constant a in (10) and the physical constant c_f can be found by using (4), (8), and (10). These give:

$$c_f = \lim_{v \to 0} f(v) = \lim_{v \to 0} \frac{v}{\frac{d\delta}{dv}} = \frac{1}{2a} \qquad (11)$$

Thus, the leading term in the expansion of $\delta(v)$ in (10) can be found from independent measurements of c_f as shown in (11).

3.2.2 High Projectile Penetration Velocities.

From the second equation in (4) and Equation (8), $\delta(v)$ can be shown to behave like the natural logarithm of v when the penetration velocity of the projectile is comparable to the acoustic wave velocity, c_p, of the target media. In this region $\delta(v)$ can be expanded as:

$$\lim_{v \to c_p} \delta(v) \approx \frac{1}{\alpha}\frac{dv}{v} = a^l \ln(v) + \frac{b^l}{v} + \frac{c^l}{v^2} + \ldots.. \qquad (12)$$

The first term in this relation -- $a^l \ln(v)$ -- was found independently by Yugoslavian researchers [15] as the best empirical fit for $\delta = \delta(v)$ at high striking velocities on glycerin soap which was used by the authors as a simulant for soft biological tissues.

The constants a^l, b^l, c^l, ... can be calculated from the experimental data for large v using a fit of the form of (12) to $\delta(v)$. Since α in (4) is related to the drag coefficient for the target medium, it is a physical parameter which by using Equations (4) and (12) can be related to the coefficient of a^l in the leading term of Equation (12). This yields

$$\alpha = \frac{1}{a^l} \qquad (13)$$

3.2.3 Solution in the Intermediate Velocity Range.

In the region of intermediate penetration velocities, the solution for $f(v)$ and the analytical fit for $\delta(v)$ can be found using matched asymptotic expansions of the functions which describe projectile penetration at low and high velocities. The matched asymptotic technique is based on the simple rule that there is an overlapping region in the intermediate velocity range where both the low velocity (Equation 10) and high velocity (Equation 12) expansions yield the same result (cf.. Figure 15). This is illustrated in Section 3.3 by examples for a sphere and a 19.6 grain flechette which are correlated with experimental results.

3.2.4 Final Polynomial Fit to *f(v)*.

After determination of *f(v)* is complete using the procedures described previously, it is then possible to fit a polynomial in *v* to obtain *f(v)*. Since the calculation of $\delta(v)$ from a fitted *f(v)* involves an integration (which is a smoothing process) as in Equation (6), estimates of $\delta(v)$ are usually very favorable. These expansions are however not valid for characterization of $\delta(v)$ using the differential relation in (7) unless the *exact* functional form of $\delta=\delta(v)$ over the entire velocity range is known *apriori*. In general this is not possible.

The tractability of using the differential relation in (7) to obtain *f(v)* can be appreciated when the complexity of $\delta=\delta(v)$ is considered. That is, $\delta=\delta(v)$ behaves as a quadratic function at low velocities where the viscoplastic properties of the target media dominate the retardation of the projectile. At high velocities fluid dynamic forces predominate and a logarithmic function is required to describe $\delta=\delta(v)$. At intermediate velocities, the target media behaves as a multiphase material incorporating both fluid dynamic and viscoplastic contributions to the retarding forces. The requirement to have a single function which is sufficiently general such that it incorporates quadratic behavior at low velocities and logarithmic character at high velocities, and that is exact is probably an insurmountable problem.

If, as is typically done for these problems, an approximation of *f(v)* is assumed, then the incorrect behavior will most likely be obtained at both low and high velocities. For example, if the polynomial fit

$$f(v) = \beta_1 + \beta_2 v + \beta_3 v^2 + \beta_4 v^3 \qquad (14)$$

is used to predict the behavior of $\delta(v)$ for high velocities using (7), Equations (15) and (16) are obtained.

$$\delta(v) \approx \frac{1}{v} \qquad (15)$$

$$f(v) \approx v^3 \qquad (16)$$

Using this approach however Equation (15) contradicts equation (12) and Equation (16) contradicts the second equation in (4). The net result is a grossly inaccurate representation of projectile penetration.

3.3 Examples of Proposed Methodology

The proposed methodology discussed in Sections 3.2.1 through 3.2.3 is implemented with respect to two examples; a spherical projectile in Section 3.3.1 and a 19.6 grain flechette in Section 3.3.2.

3.3.1 Penetration by Spherical Projectiles.

Experimental data was generated by MRC for penetration depth versus striking velocity (i.e., of $\delta=\delta(v)$) of spherical projectiles (341 mgs, 0.43 cm diameter, and 7.97 gms/cm^3) into 20% ordnance gelatin targets prepared by MRC. The striking velocity was varied between 340 and 3400 fps and penetration depth was measured in inches. A schematic of these experiments is shown in Figure 13 and the experimental data are shown in Figure 14.

Data Reduction Low Velocity Region. As indicated in Section 3.2.1, $\delta(v)/v^2$ versus v is determined from the experimental data to obtain a polynomial fit of $\delta(v)$ in the form

$$\delta(v) = v^2 \sum_{i=0}^{n} a_n v^n \qquad (17)$$

where n *is* the degree of the polynomial and the a coefficients are unknown constants to be determined by fitting a polynomial to the experimental data. For 20% ordnance gelatin and n=2, $a_0 = 5.13 \times 10^{-4}$; $a_1 = -2.844 \times 10^{-9}$; and $a_2 = 5.0 \times 10^{-13}$.

Data Reduction High Velocity Region.
For high velocity projectile penetrations, $\delta(v)$ behaves like $ln\ (v)$ and hence can be expanded as

$$\delta(v) = a^l \ln(v) + \sum_{i=0}^{n} b_i^l v^{-1} \qquad (18)$$

The a^l and b_i^l coefficients can be determined from fitting (15) to the experimental data for high projectile penetration velocities. This yields $a^l = 1.261$ and $b_i^l = 7.67 \times 10^3$. Comparisons between the low and high velocity asymptotes and' the experimental data are shown in Figure 15. As indicated in Section 3.2.3, there is an intermediate velocity regime where both the high and low velocity asymptotes yield the same penetration depths. For the data shown in Figures 14 and 15, this region is seen to lie between 2000 and 2200 fps.

Determination of Retarding Force.
Using the-low and high velocity asymptotes of $\delta(v)$ given in Equations (17) and (18) and the relation between $f(v)$ and $\delta(v)$ given in Equation (7), the retarding can be determined.

The data shown in Figure 14 can be fit with different order polynomials. Figure 16 shows $f=f(v)$ for polynomial fits of degrees 2, 3, and 4 to the theoretical $f(v)$ as determined in Figure 15. The coefficients for these polynomial fits are tabulated in Table IV.

Theoretical Determination of Penetration Depth, $\delta(v)$.
Once the theoretical distribution of $f(v)$ has been determined, the theoretical $\delta(v)$ can be resolved and the accuracy of the theoretical calculations estimated. Using Equation (6) and the polynomial fits given in Table 4, the experimental data is compared with theoretical predictions for $\delta(v)$ in Figure 17.

In Figure 17 it is shown that a cubic polynomial fit of the retardation function yields the best representation of the penetration depth and the quadratic fit yields the poorest representation. In the *Computer Man* code and derivative methodologies, as well as the format in which supporting data bases have been reduced; a quadratic form of the retardation function is assumed in the determination of penetration depth.

In an attempt to improve the fit of the quadratic $f(v)$, the coefficients in the second row of Table 4 were adjusted to yield the experimentally observed penetration depth at the maximum velocity striking tested (3400 fps). The coefficients of $f(v)$ used to achieve this are 4.0463649 E5, -941.54, and 0.72074. The resulting $\delta(v)$ from this fit is compared with the experimental data in Figure 18. From Figure 18 it is seen that the results are still not acceptable at low and intermediate striking velocities.

3.3.2 Application to Penetration by a 19.6 Grain Flechette.

Experimental results for 19.6 grain flechettes generated in Natick/MRC contract DAAK60-92-C-0003 were used to validate a code developed by MRC which is capable of determining the two-dimensional motion of a flechette when the quadratic form of the retardation force is prescribed. The code is based on modelling the flechette as a rigid ensemble of particles where the resistance to particle penetration is derived from the penetration of small spherical projectiles into water and ordnance gelatin targets. At the time of development, it was desired to develop a retardation algorithm for implementation in the *Computer Man* code. It was therefore assumed at the time of code development that a quadratic equation can adequately represent the data. Hence, a quadratic retardation force versus local velocity is employed in the code development.

The coefficients derived from Figure 18 were used in the code to compare theoretical predictions to the experimental data (see Figure 12). The results agree reasonably well despite the fact that the flechettes were fired into ordnance gelatin targets at approximately 37 degrees F by another contractor as opposed to the testing conducted by MRC to develop the data in Figure 18 which was obtained at 70 degrees F.

Figure 19 shows theoretical predictions from the code for the orientation of the flechette during penetration. Both cases are for a 1200 fps striking velocity and 6 degree striking yaw (similar to shot 15 in Figure 12). The upper plot in Figure 19 assumes an angular velocity at the time of entry in the target media of 0 rads/sec whereas the lower plot assumes an angular velocity of -0.7854 E2 rads/sec. Unfortunately, the angular velocity is never measured during wound ballistic experiments despite its importance in establishing the subsequent motion of the projectile during penetration. Given the complexity of the motion, the yaw predicted by the code was within 1.5 degrees of the experimentally observed motion established by *in-situ* measurements at four stations using orthogonal arrays of flash x-ray heads.

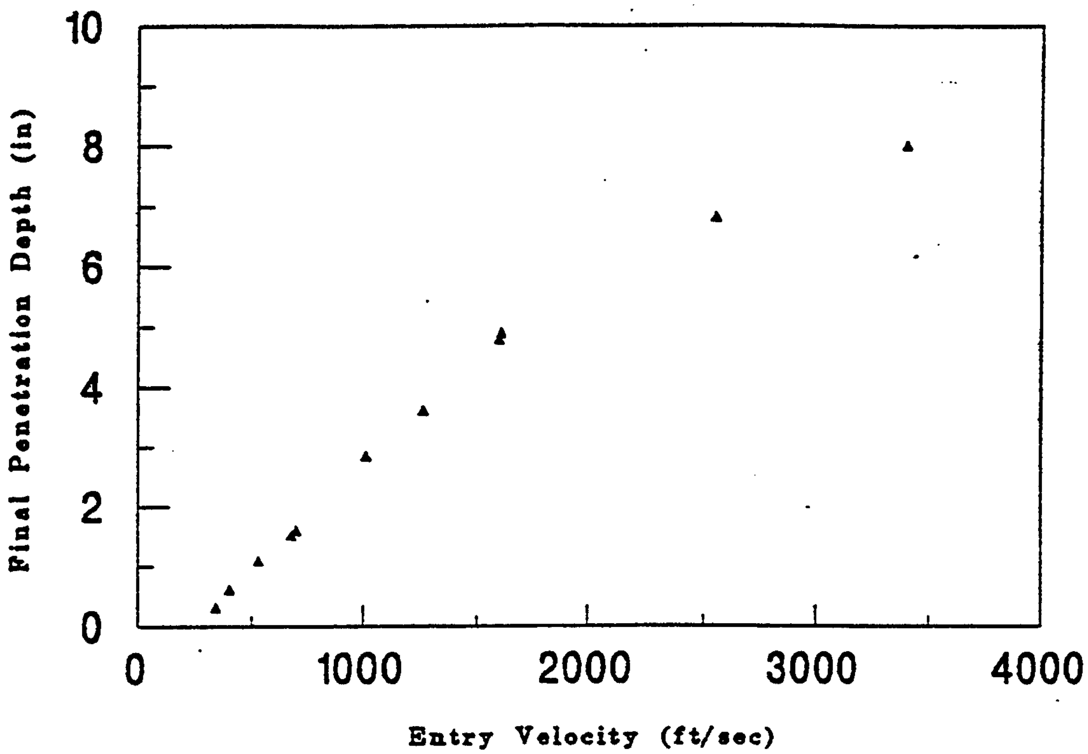

Figure 14. Experimental Data for Pentration Depth versus Striking Velocity of 344 mg Spherical Projectile into 20% Ordnance Gelatin.

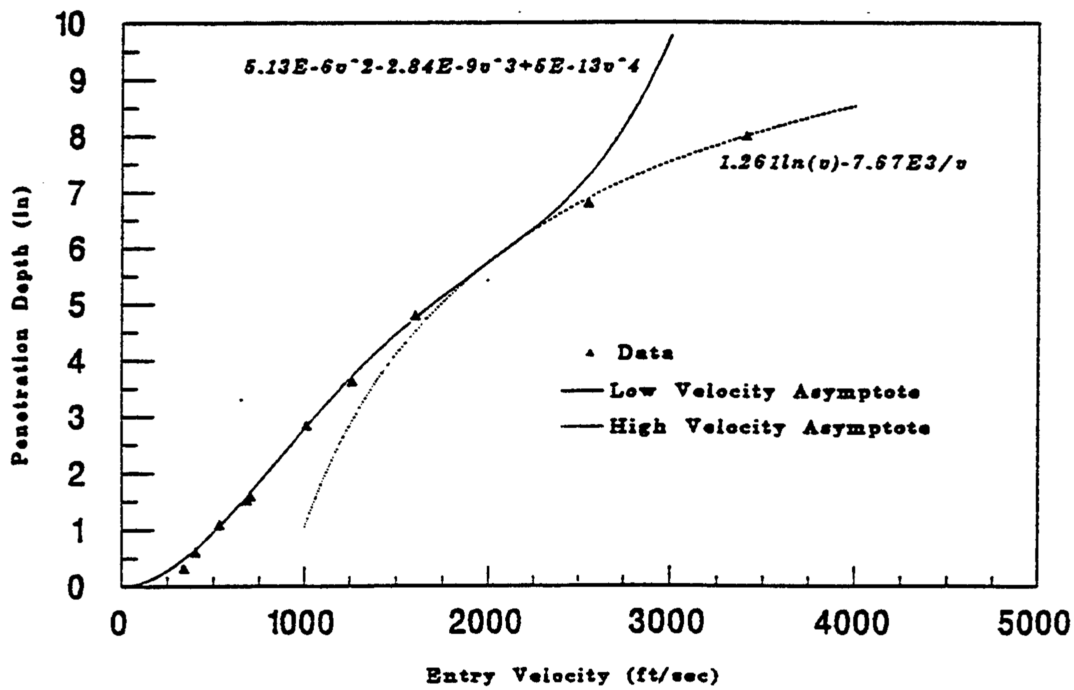

Figure 15. Comparison Between Experimental Penetration Data and High Low Velocity Asymptotes.

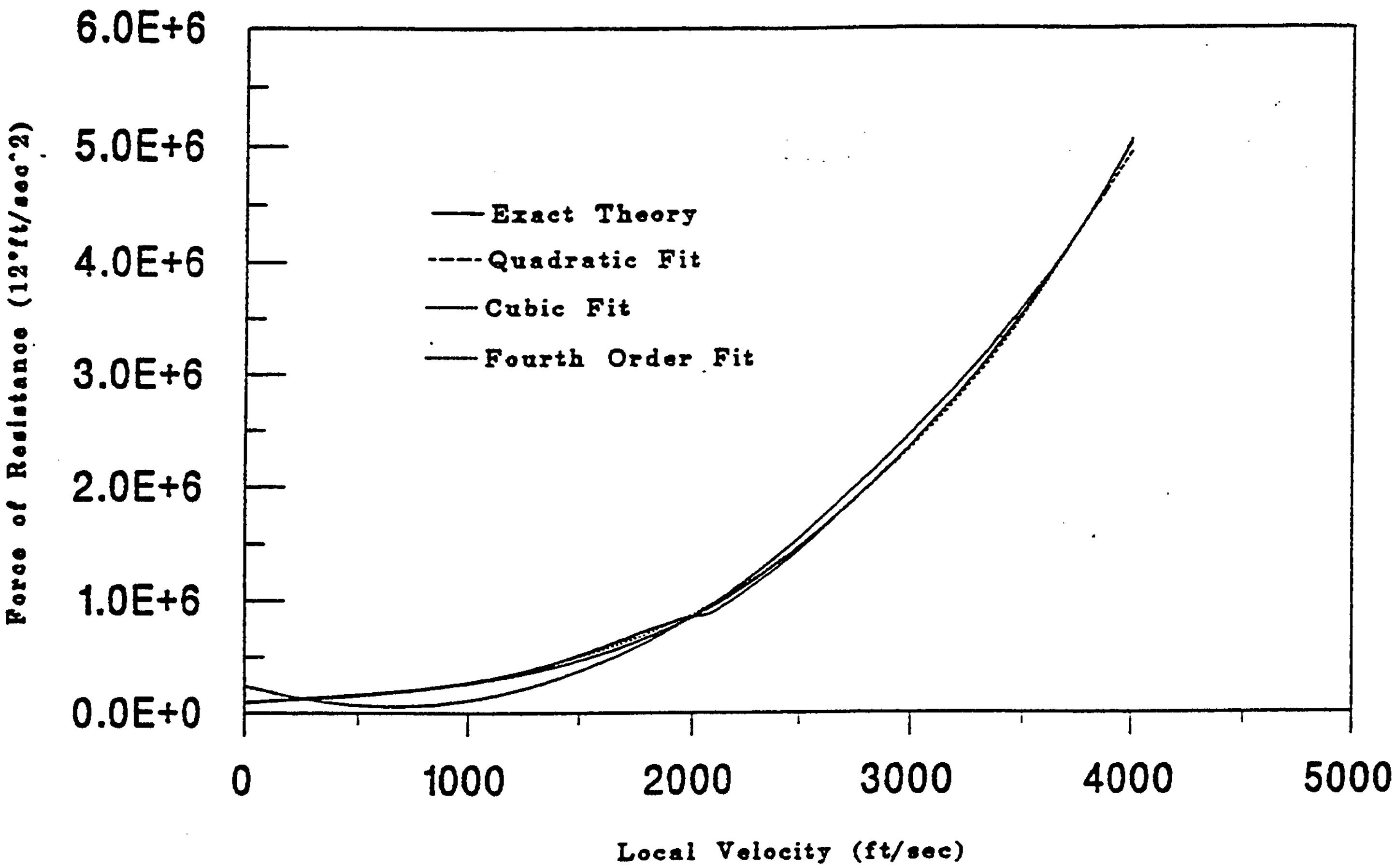

Figure 16. Theoretical Retardation Force and Various Polynomial Fits

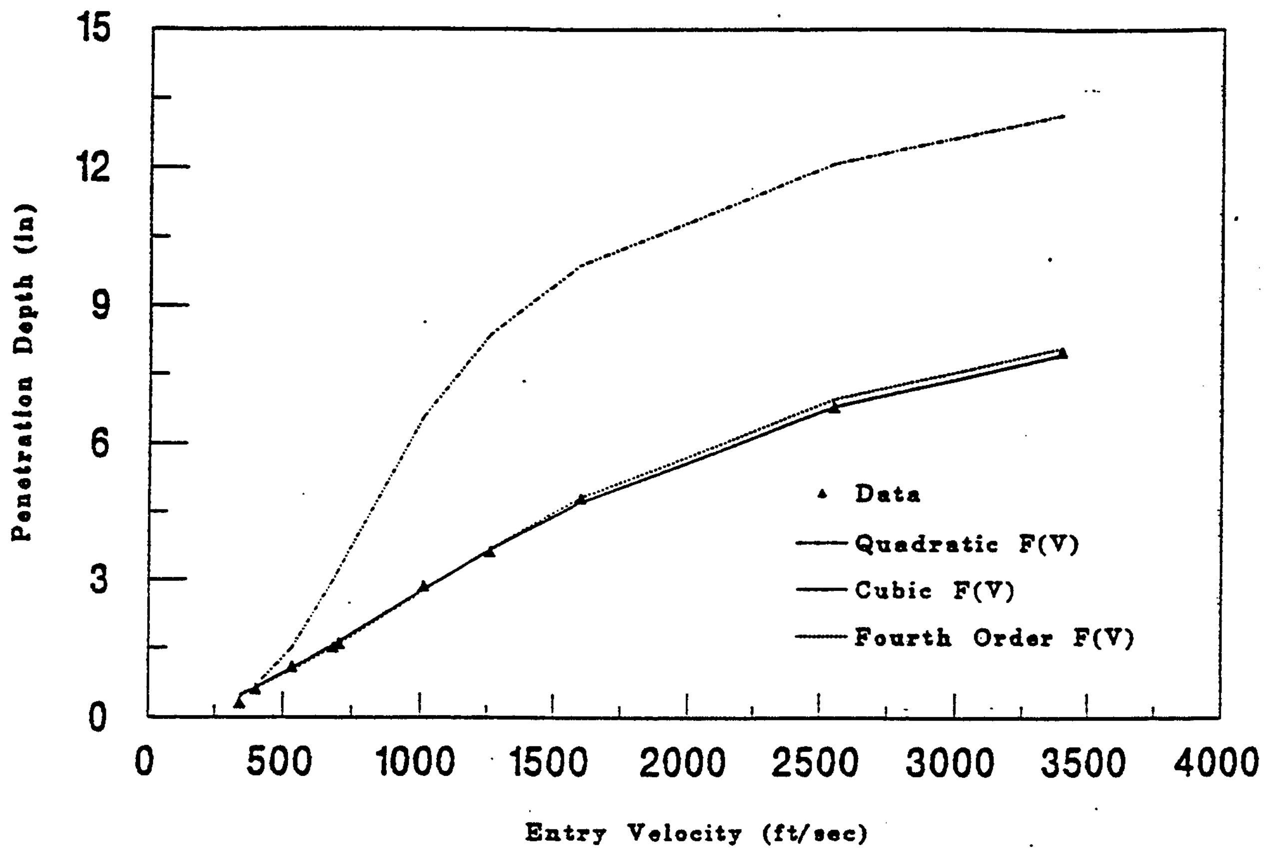

Figure 17. Comparison of Experimental Penetration Data and Theoretical Results.

Table 4. Polynomial Fit to Function Representing Retarding Force.

Degree of Polynomial Fit to *f(v)*	Constant Term	Coeff. Of Linear Term	Coeff. Of Quadratic Term	Coeff. Of Cubic Term	Coeff. Of Fourth Order Term
2	2.45234 E5	-570.63	0.043681		
3	0.94554 E5	106.4678	2.28712 E-5	7.04 E-5	
4	0.88145 E5	195.33	-0.1597	1.478 E-4	1.072 E-8

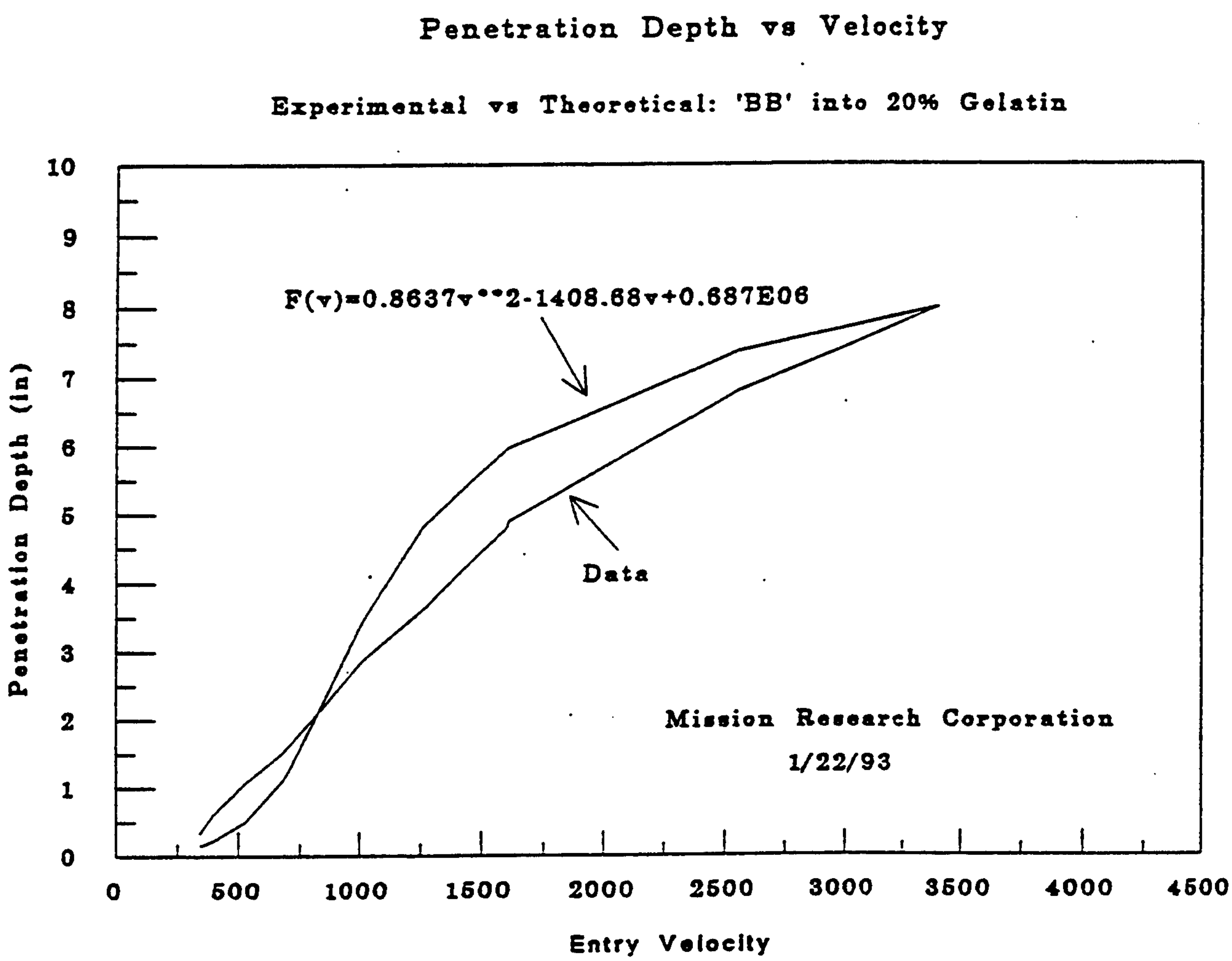

Figure 18. Experimental Data and Best Theoretical Fit With Quadratic *f(v)*

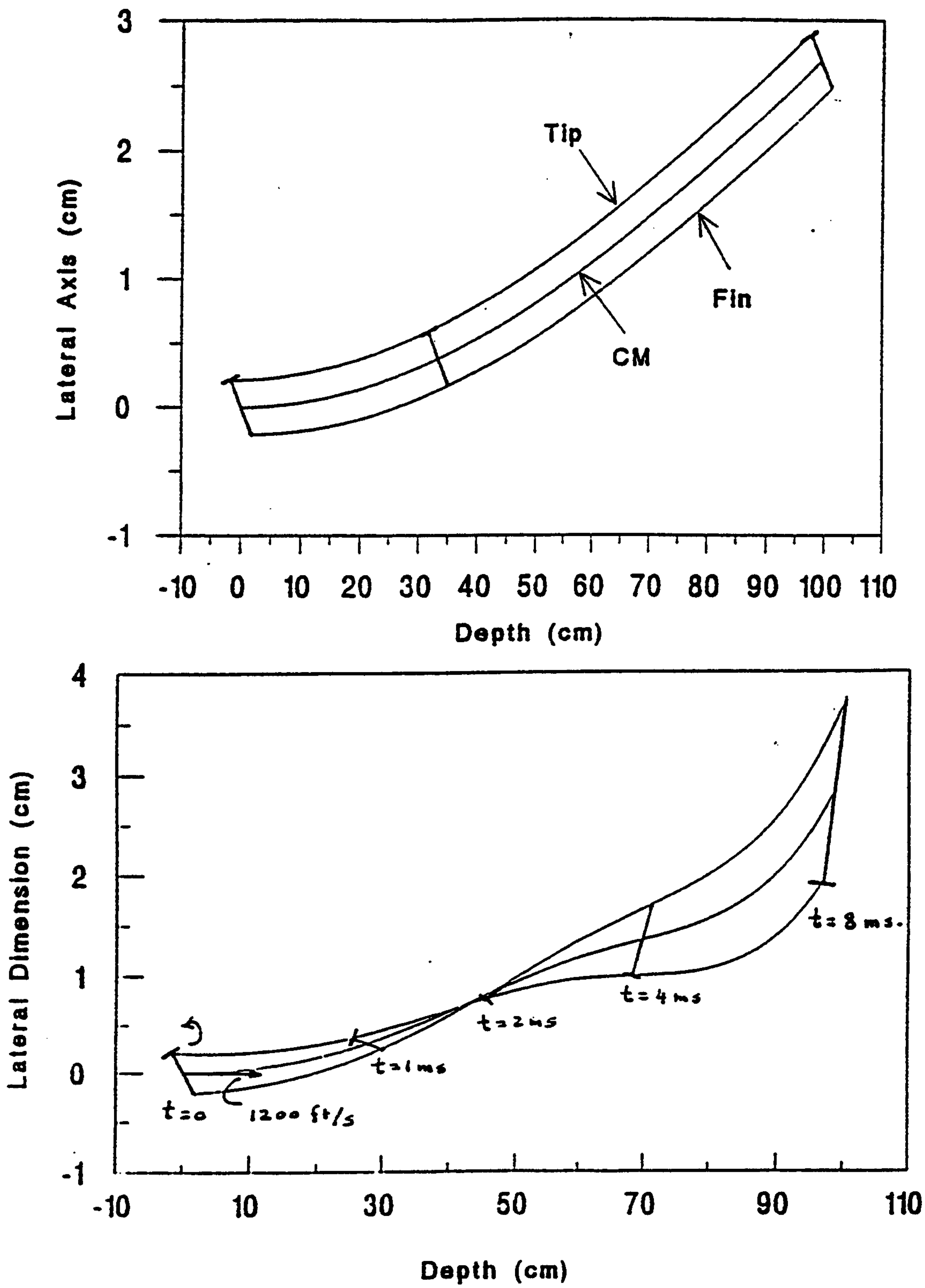

Figure 19. Flechette Motion for Different Angular Velocities at the Time of Target Entry

3.4 Summary, Recommendations, and Conclusions

In the absence of a basic understanding of the physical phenomena evident at low and high projectile striking velocities, it is not possible to model the retarding force using purely empirical methods from experimental data. In this regard, Equation (7) should be used as a guiding equation to relate the character of the two fundamental functional relations: (1) The penetration depth as a function of striking velocity -- $\delta = \delta(v_0)$; and (2) The retarding force as a function of local projectile velocity -- $f = f(v)$.

Special care should be taken when the derivative of $\delta = \delta(v_0)$ is used to obtain $f = f(v)$. Large errors can be introduced if the proper functional forms (Equations 10 and 12) are not used.

Secondly, the quadratic polynomial form of the retardation force which is used in *the Computer Man* code and derivative methodologies to obtain penetration depths and residual velocities, does not describe comparable experimental data very well.

This necessarily taints estimates of incapacitation and projectile effectiveness. It is tempting however to use a quadratic form because it appears to predict correct behaviors at high and low velocities. The problem is however to employ a functional form that can be used for intermediate velocities as well. This is where the quadratic form fails to provide correct results. Since $\delta(v)$ depends on the integral of $f(v)$, error accumulation derived from the intermediate local velocities are manifested in the incorrect prediction of the final penetration depth for a given entry velocity.

The existing data base also assumes in its reduced format a quadratic form of the retarding force, hence the existing data base may be of limited utility particularly given the lack of an audit trail and controls during the ballistic experiments.

Recommendations include data base development to obtain $\delta = \delta(v_0)$ on a standard target media involving ballistic penetration by spheres and selected ammunition. The data base development would be followed by a data reduction effort as discussed in Sections 3.2.1 through 3.2.3 to obtain $f(v)$. A key issue would be to develop the data base such that the target media and projectile properties were decoupled. This would enable the data base to be applied to other targets and striking conditions provided relevant mechanical properties of the other targets for which penetration data is not available were known.

A data base of tissue properties needs to be developed that can be exploited by the strategy above. This data base involves quasistatic elastic and strength properties, and physical densities. Wound tracts from certain handgun ammunition can also be used to develop the data base. This is based on the fact that for handgun projectiles with soft cores that tend to conserve mass and “mushroom" during penetration; a constant force model can be used to an amazing level of fidelity to predict penetration depth (+/- 1% based on limited MRC experiments [4]). Wound tract data associated with this ammunition from civilian autopsies can be used to "back-out" relevant tissue properties or to independently determine tissue properties in the data base provided the projectile is recovered and the deformation measured.

An example of this procedure involves a 22 caliber rifle bullet with a mass of 2.346 grams and a striking velocity of 1410 fps which was fired by MRC into a 20% ordnance gelatin target. This test produced a total penetration of 8 inches. Using the relation:

$$F = mv\left(\frac{dv}{dx}\right) = \frac{1}{2}m\left(\frac{v_0^2}{\delta}\right) \qquad (19)$$

where v_0, is the striking velocity and δ is the total penetration depth; an *average constant force* of 239.3 lb, would have been required to stop the bullet over this distance.

The bullet was recovered and seen to be flattened. The initial length of the bullet was 0.46 inches and the final length was 0.22 inches. This corresponds to a leading edge displacement of 0.24 inches.

Compression tests were conducted on two 22 caliber bullets to obtain the load-displacement curves shown in Figure 20. In Figure 20 it is seen that a displacement of 0.24 inches corresponds to an applied compressive load of 240 lbs. This is within 0.3% of the result using the average constant force model. This means that over a substantial region of the gelatin the bullet retards in a linear manner which is also what is observed during penetration by spheres at intermediate velocities (see Figure 14). This suggests that wounds from other projectiles can be used to derive spherical penetration data and to extract relevant *in vivo* mechanical properties (e.g., kinematic viscosity) on living biological tissues where they might not otherwise be obtained.

An example of this procedure for the 22 caliber projectile above can be shown with reference to the ballistic tests involving spheres in Figure 14. The β^l for this sphere as previously shown is 11.662. The average diameter of the 22 bullet was estimated[3] in order to render an approximate β^l (= 23.94). Using the scaling procedures discussed in Section 2.1.1 which employed the ratio of ballistic coefficients to obtain a scaling parameter; the data in Figure 14 should be scaled by 2.06 to simulate the 22 caliber bullet. At 1410 fps, the penetration depth for the sphere in Figure 14 is approximately 3.9 inches. Scaling this result to estimate the penetration of the 22 caliber bullet yields a total depth of penetration of 8.03 inches which is with 0.4% of the measured value.

The notion of an *average constant force* as applied above is a very crude model. However, the success of this model also allows the utilization of a ballistic pendulum to experimentally determine the retarding force on similar projectiles.

Another issue that has not been addressed concerns fragments which are a more prevalent battlefield threat than the projectiles discussed in this report. Modelling issues associated with fragments are perhaps less adequately addressed by the munition effects community and also more equivocal than the problems discussed previously.

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[3] The final diameter of the bullet was not measured during this test. It was estimated based on the leading edge displacement and assuming a cylindrical geometry and constant volume. This approximation yielded an average diameter ([final deformed diameter] -[initial undeformed diameter]).

This issue is being addressed with reference to geological debris and armor spall impinging on targets representative of ballistic eye protection as part of Natick/MRC contract DAAK60-91-C-0087. Standard Fragment Simulating Projectiles (FSPs) and projectiles machined from geological materials, aluminum, and steel of approximately the same mass were fired at targets representative of ballistic eye protection material cross-sections. Projectile leading edge geometries, length, and diameter as well as striking conditions were systematically varied.

Experimental results indicate ballistic limits which are very reproducible for each projectile but vary with the projectile configuration by as much as 200%. The experimentally determined ballistic limit associated with the 5.7 grain FSP is high relative to many of the other non-standard projectiles tested and therefore perhaps unconservative in terms of simulating the effect of fragment impact. A similar effort for fragments penetrating human tissues might be advised. This could be accomplished by employing tissue simulants and the methodologies proposed in this report.

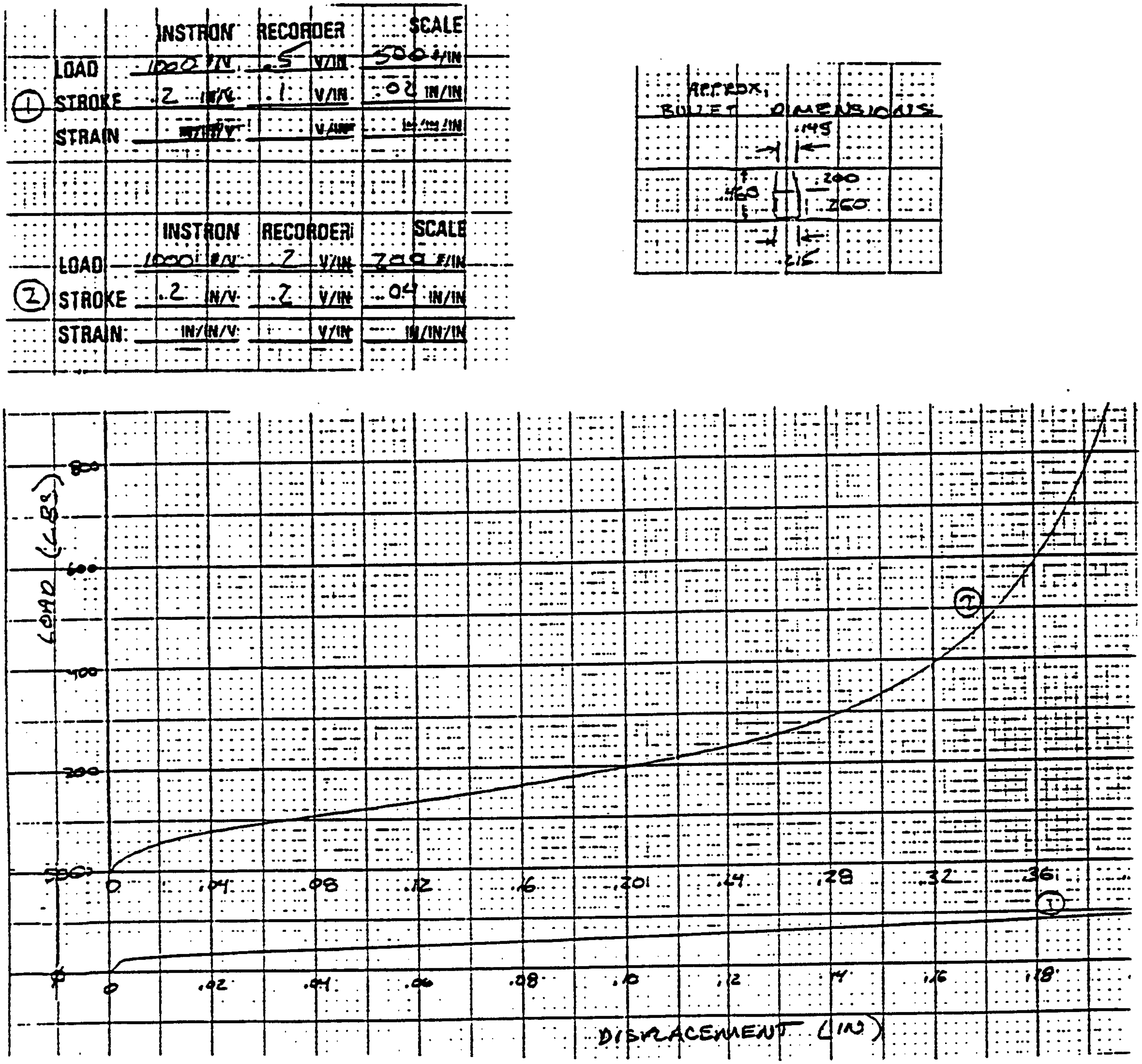

Figure 20. Load-Displacement Results for Compression tests on 22 Caliber Bullets

This document reports research undertaken at the U.S. Army Soldier and Biological Chemical Command, Soldier Systems Center, and has been assigned No. NATICK/TR-01/011 in a series of reports approved for publication.

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APPENDIX

Preparation and Testing of Ordnance Gelatin

BACKGROUND

The purpose of the ordnance gelatin specimens in the present effort is very narrow relative to their nominal use in the wound ballistics community. In the wound ballistics community, ordnance gelatin is ordinarily used to simulate the wound tract and/or deposition of kinetic energy in skeletal muscle tissue subject to ballistic penetration. A key issue in these experiments is the fidelity of the ordnance gelatin target relative to reproducing the wound tract in soft tissue. This issue is key since the experimental results are often used to produce a database from which empirical models and relations can be developed.

The quantitative relation between the dimensions of the wound tract in tissue and the cavity promoted in the gelatin target subject to ballistic impact is not an important consideration in the subject effort. Rather, the purpose of the ordnance gelatin is to simulate phenomenologically different aspects of the projectile-tissue interaction and identify how parametric changes in the properties of the gelatin affect the "physics" of the interaction. These experiments can then support development of analytical models which will posses the appropriate parametric form for biological tissues. Further, the parameters in the resulting analytical models can be related to physical properties and therefore can be explicit functions of tissue properties.

Key issues in the ballistic experiments performed by MRC are that: (1) The phenomenology of projectile-gelatin interaction simulate relevant aspects of the soft tissue-projectile interaction; (2) Relevant mechanical properties of the gelatin targets, as well as in the corresponding tissues, can be identified and quantitatively characterized; and, (3) With respect to the mechanical properties identified and characterized in item 2, the gelatin targets can be made with verifiable consistency and remain stable over time with respect to the mechanical properties of interest.

If these issues can be satisfactorily addressed then the parametric forms of the analytical models developed for the gelatin targets can be used to describe soft tissue response to ballistic penetration with tissue properties substituted for the appropriate parameters.

The ballistic targets employed ordnance gelatin powder, type 250A, and was obtained from Kind & Knox in Sioux City, Iowa. Both 10% and 20% gelatin formulations were investigated. Preparation guidelines described by Fackler and Malinowski (1988) of the Trauma Research Center at the U.S. Army Letterman Institute, Reference 1A; Lewis, Clark, and O'Connell (1982) of the National Naval Medical Center, Reference 2A; Keenan (1990) Associate Director of Research and Development of Kind & Knox, Reference 3A; and Winter and Shifler (1975) contractors to BRL, Reference 4A; were followed and compared. Gelatin formulations used in this effort are summarized below.

Batch 1 (Fackler and Malinowski. Reference 1A)
The procedures followed in the preparation of Batch 1 include hydration in 45 degree F water for 2 hours, heating to 104 degrees F maximum, and curing for 36 hours. Fackler and Malinowski also warn against the use of excessive heat in the preparation process and list specific procedures and conditions to be avoided.

Batch 2 (MRC/GBL variant of Fackler and Malinowski)
Deviations from the procedures described by Fackler and Malinowski were then used to produce Batch 2 in order to expedite the preparation process. These deviations include dissolving the gelatin powder in 104 degree F water and curing for 36 hours.

Batch 3 (Lewis, Clark. and O'Connell. Reference 2A)
Batch 3 was produced following the procedures of Reference 2A and included dissolving the gelatin powder in 180 degree F water and curing for 36 hours. This procedure was identified in Reference 1A as unacceptable.

Additionally, various aspects of the procedures advocated by Winter and Shifler, Reference 4A, were evaluated. These procedures, discussed in Reference 4A call for mixing in 25 degree C water, hydration for 1 to 3 hours, heating in a 65 degree C bath until the gelatin is 61 degrees C then heating in 45 degree C bath for 40 minutes, and finally chilling in 10 degree C bath for 16 to 18 hours.

During the course of this effort it was discovered that the agglomeration problem identified in Reference 4A when mixing in 25 degree C water could be avoided by mixing in 10 degree C water. Further, ballistic tests performed on various gelatin specimens cured for different lengths of time indicated that the gelatin targets required at least 36 hours to fully cure at which time the ballistic properties seem to be stable if the specimen is not allowed to dehydrate.

The three batches described above were produced in both 10% and 20% formulations and were ballistically tested using 0.1694 inch diameter, 0.345 gram copper coated steel BBs. Penetration depths were measured and were seen to be independent of the gelatin preparation process. Additional observations from these tests are listed below.

(1) Better optical clarity resulted when the powder was hydrated in cool water.

(2) Significantly reduced foaming occurred during powder wetting when cold water was used (water temperature 60 - 65 degrees F).

(3) The 36 hour curing (aging) process appears to be critical. Gelatin specimens tested after 12 hours produced significantly deeper penetration than fully cured targets. For gelatin specimens older than 36 hours, penetration depth appeared relatively insensitive to aging.

Based on these observations, a less labor intensive procedure which preserves the quality, consistency, and stability of the gelatin targets was employed in subsequent testing.

These procedures include hydrating the gelatin powder with 60 - 65 degree F water in a Hobart mixer. The Hobart mixer used for the MRC gelatin preparation was modified with a rheostat to run at about one half of the lowest mixer speed. Under these circumstances, the agglomeration observed during early phases of the mixing is not significant. The gelatin also was allowed to stand for 2 hours, heated to approximately 110 degrees F, then cured for 36 hours at 45 degrees F.

In the interest of conserving raw materials and reducing processing time the feasibility of melting and re-solidifying a block of gelatin after ballistic testing was also investigated. A previously tested block was melted and re-solidified. After the gelatin was aged for 36 hours, the appearance and ballistic properties of the block was seen to be identical to the original gelatin target. This block was then re-melted, aged, and re-tested again resulting in penetration depths that were also identical to the original gelatin target. Based on these limited experiments using a 20% gelatin formulation, it seems as though the gelatin targets can be re-used provided that no biological degradation has occurred (mold growth).

The following observations were also made during the course of this investigation.

(1) Gelatin cast in stainless steel molds exhibited rather poor surface qualities and the non-parallel side walls complicated testing and accurate data retrieval. Plexiglass molds with parallel walls were fabricated and used in the gelatin preparation. This resulted in very good surface qualities which rendered the blocks far more transparent and minimized diffraction effects. This was important for enhancing photography and optical diagnostics as well as enhancing the accuracy of measurements inside the gelatin.

(2) Gelatin in contact with air forms a rather tough surface layer of dehydrated gelatin which does not have properties representative of the gelatin cross section. Exposure to air should therefore be minimized. Wrapping blocks in clear plastic film was found to be effective in preventing the formation of this surface layer.

(3) The surface integrity at the entry site for the projectile is extremely important and significant stand-off distances of projectile trajectories from pre-existing damage should be maintained.

The importance of surface integrity cannot be over-emphasized. The gelatin was found to have a surprisingly high resistance to the onset of penetration; i.e., permanent deformation in the gelatin did not occur below a threshold velocity. This threshold velocity for 20% gelatin was found to be 250 fps for BB's of the type described. Once penetration was effected however the magnitude of this threshold did not seem to bias projectile retardation.

This last conclusion was inferred from two series of ballistic tests using BBs. The first series involved a monolithic homogeneous gelatin target. The second series involved a multilayered gelatin target which was layered perpendicular to the projectile trajectory. The multilayered targets consisted of two configurations of gelatin where each configuration included the same integrated thickness of gelatin. In the first configuration the gelatin layers were in intimate contact. In the second configuration, the gelatin layers were separated by air-gaps. Although total penetration distance was greater for the targets which incorporated the air-gaps, the integrated depth of penetration into the gelatin was the same for both configurations.

It was also found that a block of gelatin was resistant to tearing when the outer surface being stressed was un-flawed. When a small surface slit was introduced, tearing was easy and the resulting defect could be easily propagated through the entire block.

A series of tests was also conducted using spherical projectiles (BB's) to establish maximum penetration as a function of striking velocity. The following important observations were made during these tests.

1. The maximum penetration depth varied linearly with striking velocity after a threshold velocity was exceeded. This was true up to the maximum striking velocity tested (1300 ft/sec). This observation held for 10%, 17%, and 20% gelatin provided that temperature was constant throughout the gelatin target and maintained to very exacting tolerances.

2. The maximum penetration depth depended on target temperature for the different formulations of gelatin. Targets with a higher percentage of gelatin (20%) exhibited a much weaker temperature dependence than targets with a low percentage of gelatin (10%).

Temperatures were varied 10 F degrees, from 37 to 47 degrees F (except for the 17% gelatin). The change of penetration depth with temperature is seen to be nearly constant for 10% gelatin targets subject to striking velocities of 400 and 530 ft/sec. For incident velocities of 270 ft/sec, a weaker dependence is evident. This may be attributable to measurement uncertainties in the initial gelatin targets (made in steel molds) which did not have absolutely parallel surfaces.

The maximum penetration depth as a function of temperature is about 0.065 inches/degree F in 10% gelatin and about 0.004 inches/degree F in 20% gelatin for the temperature range evaluated.

The dependence of penetration depth on temperature in gelatin targets suggests a need for testing in a temperature controlled environment with the gelatin target in thermal equilibrium. The thermal conductivity of the gelatin, as alluded to in Reference 1A, appears to be very low. However the low thermal conductivity of the gelatin also suggests a low thermal diffusivity which could lead to large thermal gradients (depending on ambient conditions). This makes some measurements on the 10% gelatin formulations reported in Reference 1A, which were accomplished over a 90 minute time period, questionable. Finally, it seems that the gelatin targets may undergo surface cooling due to evaporation of water from exposed surfaces. This could render small numbers of infrequently made temperature measurements at widely separated locations in error.

3. The maximum penetration depth for standard BB's into 10% and 20% ordnance gelatin exhibits (within the low to intermediate velocity range tested) a linear velocity dependence after the threshold velocity has been exceeded. The maximum penetration depth is also seen to vary linearly with velocity from the threshold penetration velocity to the highest value tested (1260 ft/second). As expected, the absolute penetration depths are far greater in the 10% gelatin than in the 20% gelatin. Also the change in penetration depth with velocity is also significantly less for the 20% gelatin.

The data presented in Figures 2, 3 and 4 clearly shows that for spherical particles, over the velocity range tested, the maximum penetration depth varies as a linear function of velocity. The resistance law that will describe the deceleration of the projectile will therefore also vary with velocity to the first power plus a constant. In the current model, the resistance law is assumed to be a quadratic function of velocity, i.e., $F = AV2+ BV+C$. The present data suggests that A must be zero (or close to zero for the velocity range evaluated). This contradicts results reported in References 1A and 2A.

The linear dependence of the drag suggests a drag coefficient which is dependent on $1/v$ and a Stokes flow regime which is dominated by viscous drag. In Stokes Flow, applicable for Reynolds numbers of order 1 and below in air, the drag coefficient is inversely proportional to the Reynolds number (or, kinematic viscosity divided by velocity).

Without attempting to justify its application to this problem, an equivalent kinematic viscosity for the gelatin employed in the testing above was found to be on the order of heavy engine oil. This interpretation seems credible and no doubt applicable over the low velocity range tested and limited to spheres.

In the testing described above, the various sensitivities described in Reference 1A were not apparent. While it is desirable to wet or hydrate the powder at tap water temperature or below; the issues of whipping or rapid stirring were viewed as practical problems to reduce foaming but could not be shown to affect the ballistic response. Further, it is not recommended to wipe off the foam since it appeared to return into solution over time. The deterioration of the gelatin associated with exposure to temperatures above 104 degrees F could not be confirmed. When the gelatin powder was mixed with water at about 180 degrees F a lot of foaming was evident and also evaporative water loss. The gelatin end product turned out to be more cloudy however but changes in ballistic performance were not evident.

The most important parameters identified in this preliminary study to ensure consistent ballistic performance for the gelatin targets were: (1) Aging of blocks for at least 36 hours; and, (2) Careful temperature control during testing, especially for gelatin formulations less than 20%.

RECOMMENDED PREPARATION AND TESTING SPECIFICATIONS OF ORDNANCE GELATIN

It has been suggested that a large number of different mixing and aging procedures used in preparing ordnance gel will effect it's penetration resistance to ballistic impacts. An attempt was made here to address the importance of these parameters on the penetration resistance of gelatin. Gelatin blocks were judged to be equivalent when the penetration depths of standard BB's were identical (within +/- 2%) for identical striking velocities. We highly recommend that each gelatin block be subjected to a standard BB impact at a reasonable velocity, say 1,000 feet per second, to establish the pedigree of the gel before additional data is generated.

The tests conducted here did not confirm the sensitivity of the ballistic response of gelatin to the large number of mixing and environmental parameters identified in the literature. Some of these parameters did affect the ease of preparing the mix but failed to produce significant differences in the ballistic response. The only parameter/procedure identified to have a significant effect on the ballistic response was aging/curing of the gelatin. In addition, a strong dependence of penetration depth on gelatin temperature was identified for 10% mixes with a relatively mild dependence for 20% gelatin. For low concentrations we recommend target temperature control rather than monitoring during impact testing because the low thermal diffusivity of this material can support significant temperature gradients.

The procedures recommended here and outlined below include a number of procedures that will simplify the mixing process and facilitate control, but are not necessary to assure consistent ballistic response.

RECOMMENDED PROCEDURE

1. Blend powder into cold water, 5 to 10 Degrees C, by slow stirring. (Low water temperature reduces tendency to form clumps and slow stirring reduces foaming).

2. Allow whetting or hydration to take place for nominally 2 hours. (Insufficient hydration will result in clumping during subsequent heating cycle).

3. Heat mixture slowly (hot water bath - double boiler is recommended) to 40 to 50 Degrees C. Do not use a flame or hot plate to heat mixture directly. (Heating up to 90 Degrees C had no effect on ballistic performance - We advise against high temperatures during this phase however to limit the amount of water lost to vaporization).

3\. Cure mixture for at least 36 hours in a refrigerator at 8 to 10 Degrees C. (We did not specifically explore the importance of cure temperature but saw no difference for temperatures between 8 and 12 Degrees C.

5. Avoid vapor loss from block. (A tight wrap or cover is recommended to avoid moisture loss from free surfaces and skin formation).

6. Confirm that entire block is in temperature equilibrium before testing, especially for low concentrations. (Temperature effects were shown to be large for 10% and small for 20% gel)

7. Perform a standard BB impact test to confirm ballistic response before starting testing.

In the interest of conserving materials and reducing preparation time, we conducted an exploratory investigation to see if gelatin could be re-used. To this end we re-melted a block and re-formed it by the above procedure. No change in the ballistic response was noted. A second attempt to re-melt and re-mold also produced no change in the ballistic response but the optical clarity of the block was becoming progressively worse. Please note that these tests were conducted on 20% gelatin only and may not hold for other formulations.

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